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THE JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY

CONTENTS **DECEMBER 1952**

SECRETARY'S NEWS LETTER AND NOTICES

PROBLEMS OF SERVICING AND RELIABILITY
Group Captain G. M. Buxton, O.B.E.

THE DESIGN AND CONSTRUCTION OF AIRFIELD PAVEMENTS
M. J. Tomlinson, A.M.I.C.E., A.M.I.Struct.E.

OSCILLATORY OCCURRENCES IN BALL BEARINGS
Dr. M. S. Frenkel

CORRESPONDENCE REVIEWS ADDITIONS TO THE LIBRARY

INDEX TO VOLUME 56, 1952

LONDON

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And no Doodling

BY BERNARD HOLLOWOOD

THE fuels used in gas turbine-engined aircraft consist almost entirely of hydrocarbons—that is, of compounds of hydrogen and carbon. Five or six of carbon to one of hydrogen, or thereabouts.

Now some of the patterns formed by these atoms of 'H' and 'C' are extremely pretty and decorative, but they're not exactly the result of doodling. Modern aircraft are dietetically very choosy: their intake of fuel must be exactly right, perfectly blended and balanced, with no roughage.

Otherwise there's trouble.

If the 'H's and 'C's don't add up satisfactorily the fuel will not burn cleanly and efficiently, and free carbon will be formed. Dirty, self-advertising smoke will emerge from the exhaust (the R.A.F. take a poor view of this phenomenon) and ruinous deposits may appear in the engine combustion system.

So no doodling: the pattern must be precise, the regimen exact.

All crude oils contain sulphur, and sulphurous fumes are no good for an aircraft's digestion. They corrode the works. So fuel manufacturers take infinite pains to eliminate excess 'S.' The crude oils imported from the Middle East are exceptionally rich in sulphur—yes, *rich*: you see, the sulphur extraction plant at ESSO's new giant refinery at Fawley (near Southampton) is so efficient that 'S,' once an unmitigated nuisance, has become a valuable by-product and a prop to the national economy.

And another thing—aircraft engines like their fuel volatile, more volatile in fact than can normally be handled by the aircraft's tankage and pumping system (there's such a thing as "vapour-lock"). The fuel is helped to vaporise, to mix with air and to burn steadily by being injected into the engine's combustion chambers under high pressure.

Fuels that "go steady" are the common objective of the men who design ESSO products, and aircraft engines: they want their fuels to burn quietly, stably and effectively under all conditions—particularly those encountered at great heights where pressure and temperature are not. High-climbing aircraft must be able to "idle" steadily when on the roof so that they can be brought down without gathering too much speed. That's important.

Once again it's the pattern that matters, the arrangement of the fuel components, the 'H's, the 'C's and the etceteras. So there's no doodling in the ESSO laboratories—or did we say that before?

Improvements in aircraft performance must be preceded by improvements in fuel performance, which, in turn, must be preceded by unremitting research and experiment.

All of which can be followed, in turn, by the categorical statement that—

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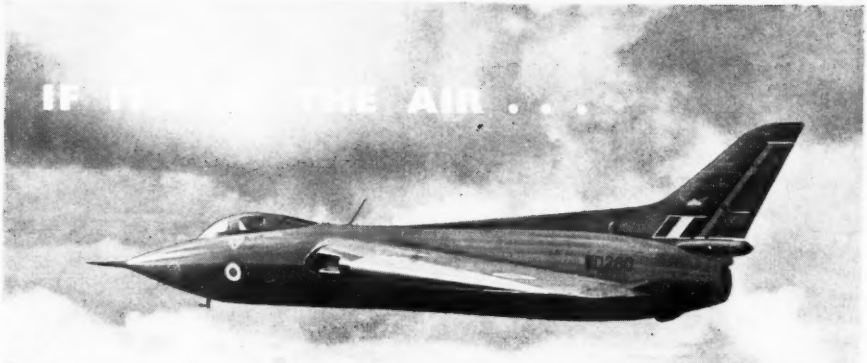

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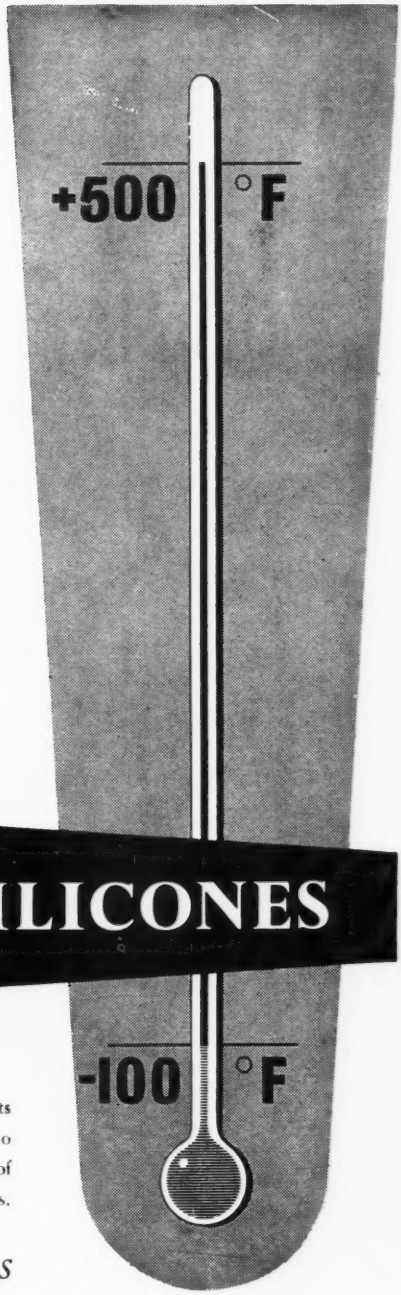

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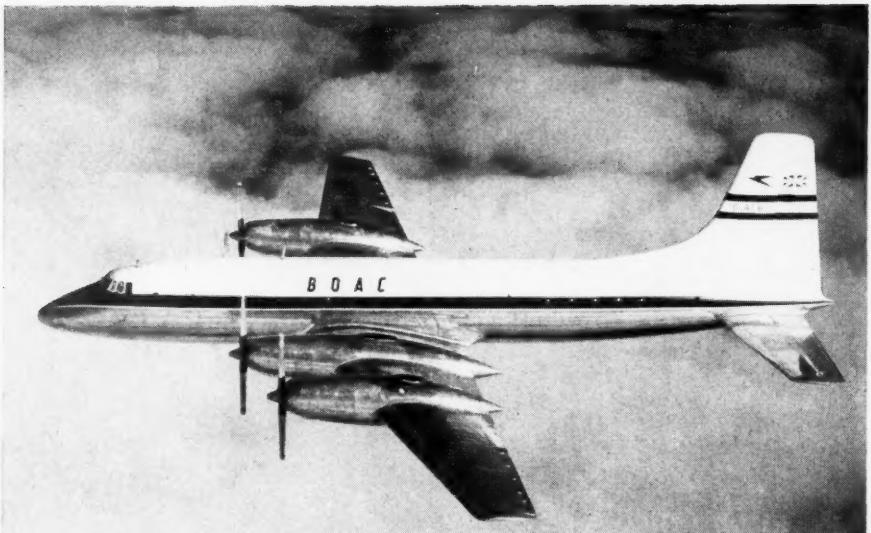

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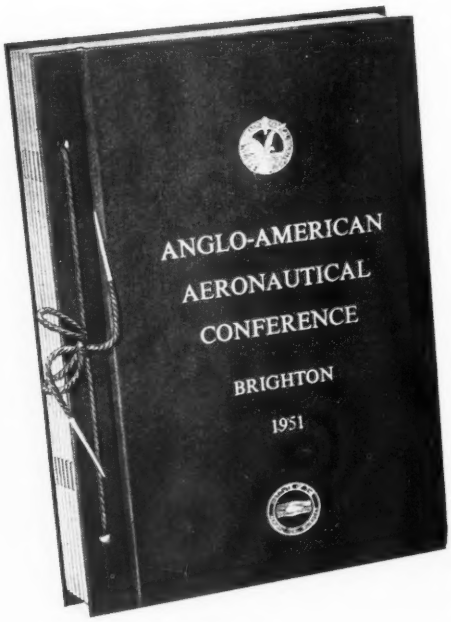

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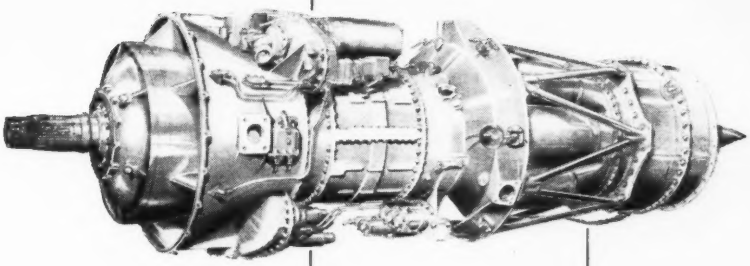

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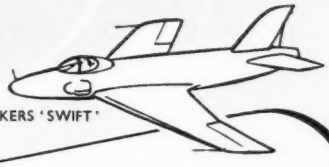

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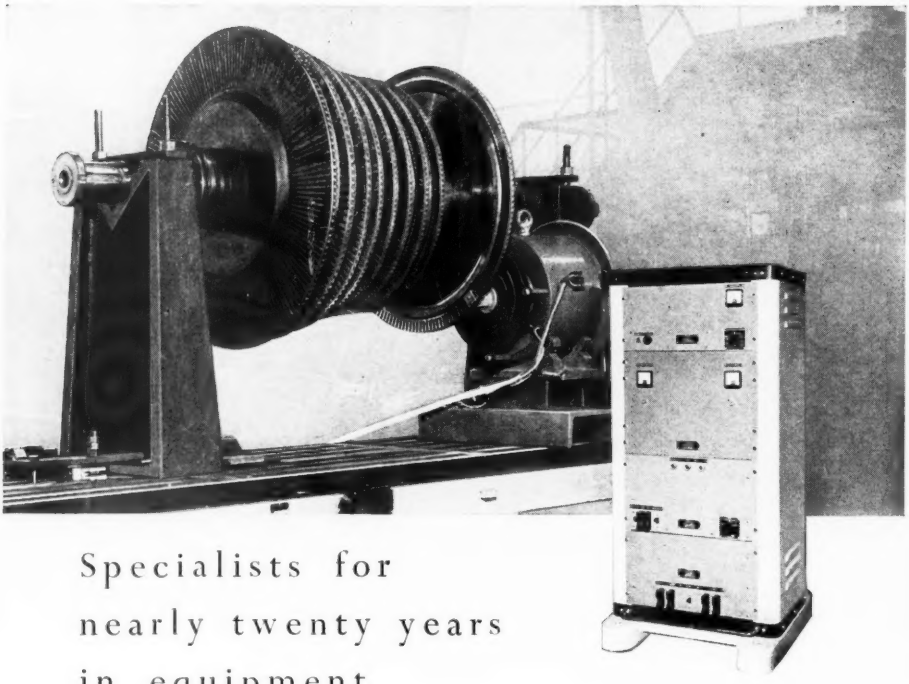

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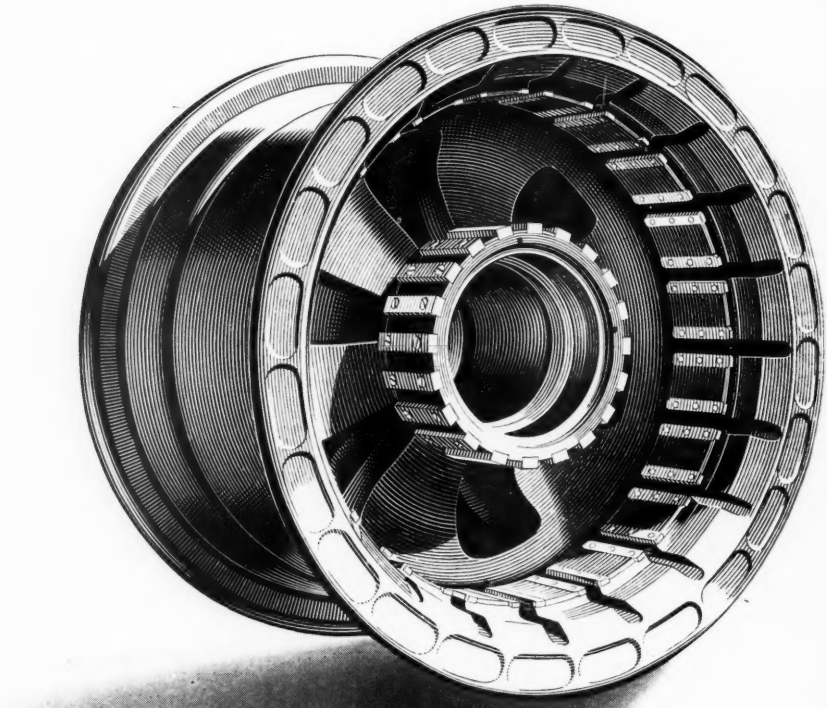

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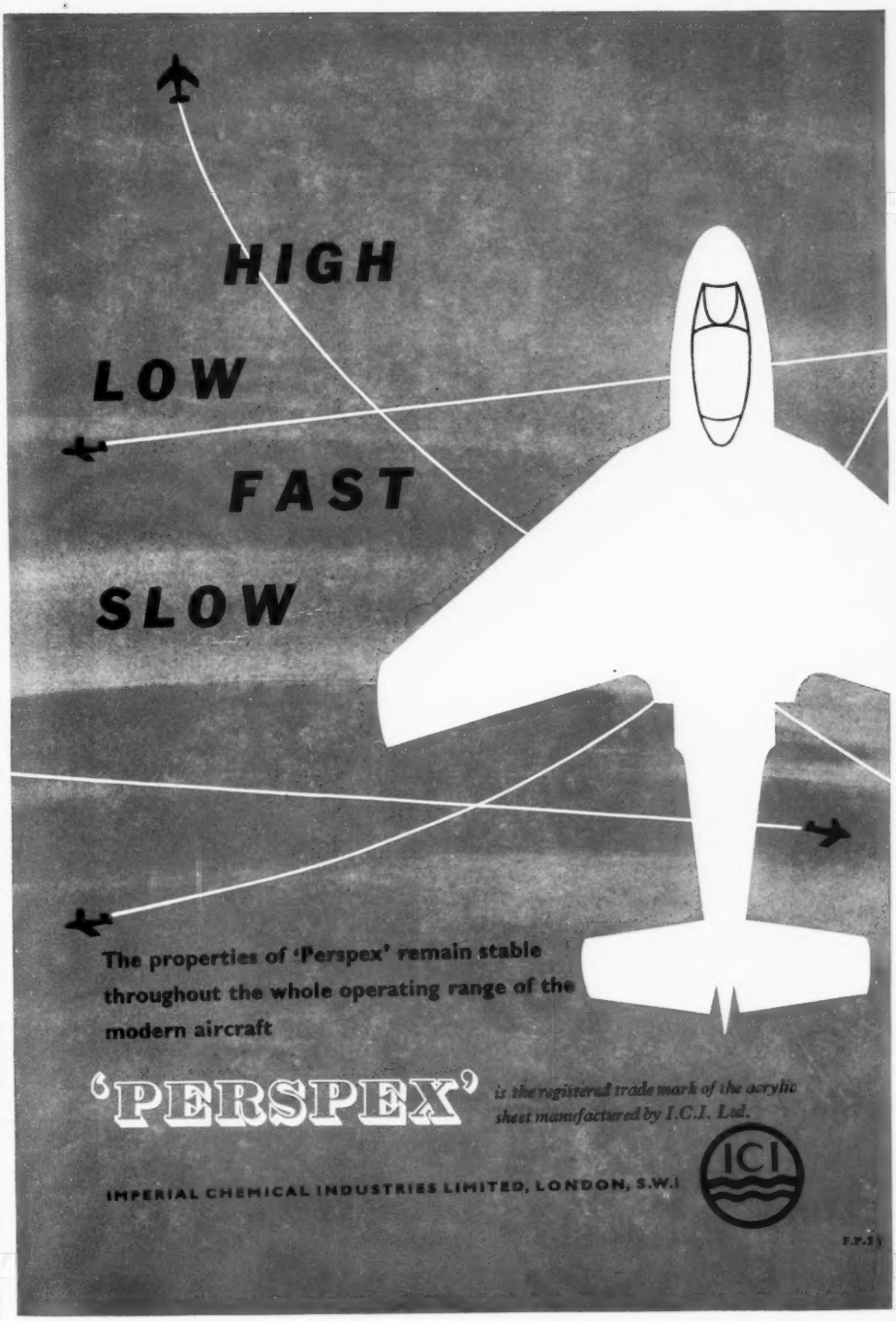
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The Council have set aside an annual sum of £250 for the award of premiums for papers published in the JOURNAL. Both members and non-members are invited to contribute original papers on their own special subjects. The following notes on the preparation of papers for the JOURNAL are given to assist contributors:—

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The copyright of every paper printed in the JOURNAL shall be the property of The Royal Aeronautical Society. If the author makes use of copyright material in his paper or information obtained by reason of his employment or otherwise, he must state clearly in his covering letter, or in the paper, that consent has been given for the use of such material.

MANUSCRIPTS

Papers must be in English, in the third person, and typed on one side of the paper only, with double spacing and wide margins. When submitted they must be in their *final form for publication*. Only typographical errors may be corrected in proofs. Titles of papers should be brief.

Where practicable, a summary of not more than 250 words should be given at the beginning of the paper, giving its scope and conclusions.

All references should be numbered in the text where they occur, and the complete list of references given at the end of the manuscript. These references will be published at the end of the text. Footnotes should be numbered consecutively. Tables should be kept as concise as possible.

ILLUSTRATIONS

Illustrations should be drawn so that they will reduce to column or two-column width, that is to 2⅝ or 5½ inches. Full page illustrations must reduce to 5½ inches by 8 inches. All drawings must be in black ink on white paper or tracing cloth.

Lettering and figures on drawings must be in pencil only. Drawings should be posted flat or rolled.

Photographs should not be less than half plate in size and must be clear black and white glossy prints.

Every drawing and photograph should have on its back its figure number and title.

MATHEMATICS

Only very simple symbols and formulae should be typewritten. All others should be written carefully by hand in ink. Ample space for marking should be allowed above and below all equations. Greek letters should be designated by name in the margin.

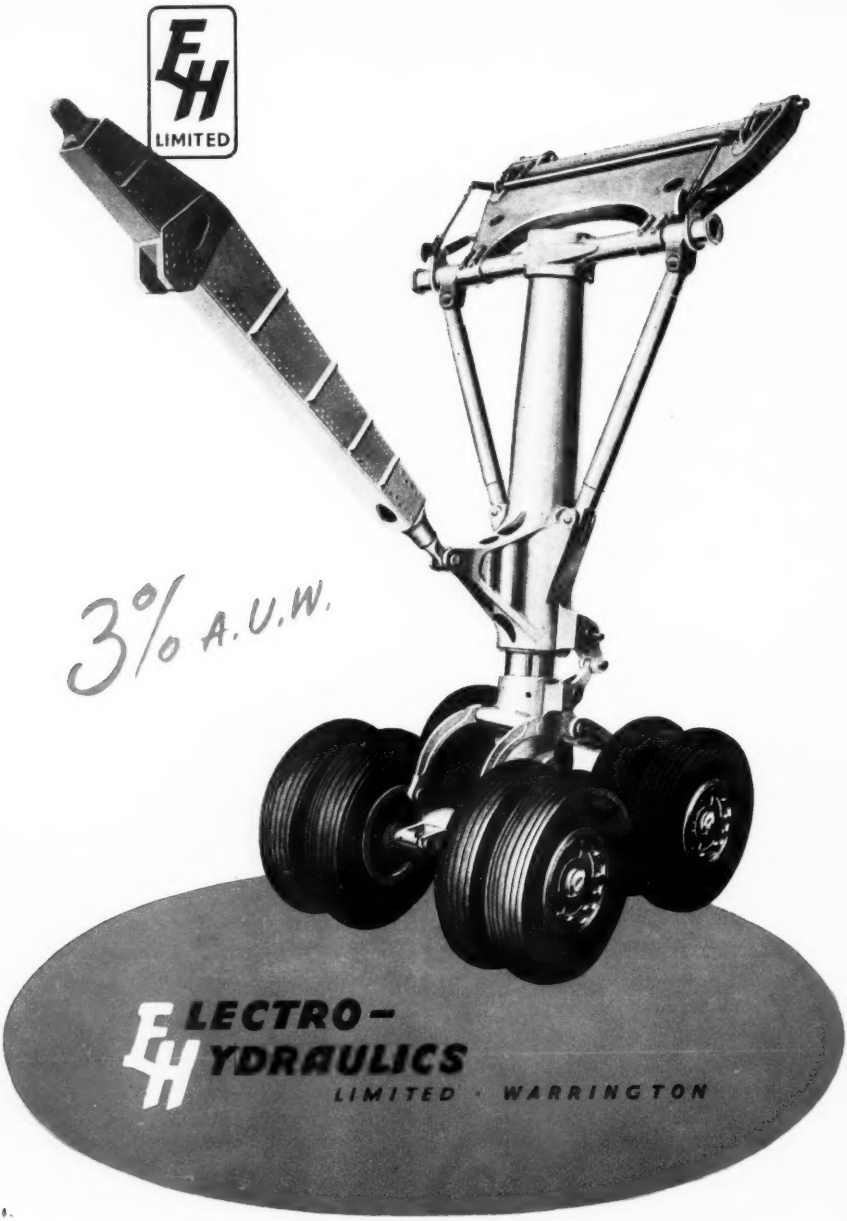
The difference between capital and lower-case letters should be clearly shown; care should be taken to avoid confusion between zero (0) and the letter o, between the numeral one (1) and the letter l, between alpha and a, kappa and k, mu and u, nu and v, eta and n.

All subscripts and exponents should be clearly marked, and dots, bars, and so on, over letters should be avoided as far as possible.

Square roots of complicated expressions should be written with the exponent ½ rather than with the sign $\sqrt{}$.

Complicated exponents and subscripts should be avoided. Any complicated expression that recurs frequently should be represented by a special symbol.

Unless an abbreviation is one recognised as standard practice, both in this and other English-speaking countries, for example b.h.p. for brake horse power, the meaning should be given in full on its first use.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Secretary's News Letter

DECEMBER 1952

IN January the JOURNAL will be increased in size, and this is therefore the last of the present format. I think that the new size will make the presentation more attractive, with considerably more scope in layout and, it is hoped, in the long run, that it will mean a saving in production costs.

No doubt there will be many who will regret the change but I hope that the future Journal will be an even better and more useful publication.

In the News Letter last month I mentioned the foundation of two new Branches, one at Merthyr Tydfil and one at Henlow. I have attended the inauguration of both.

The President was present at the Merthyr Tydfil meeting, and welcomed the new Branch with appropriate words. Dr. E. W. Still, one of the foundation enthusiasts, the temporary chairman, was confirmed in his office; Mr. G. M. Magill was elected Secretary; Mr. W. F. F. Martin-Hurst was unanimously voted President of the Branch. The evening was rounded off by showing Mr. E. D. Stout's films on flying boats from the 1951 Anglo-American Aeronautical Conference.

Unfortunately the President was unable to be at the Henlow Meeting on 4th November, but Major G. P. Bulman was an able and appropriate substitute; he it was who some years ago, started the idea of a Henlow Branch.

The meeting went in Service fashion. I know that I should be maligning Group Captain W. R. Worstall were I to say that the details were a result of "detailing"; from this you can gather that everything went with the precision of the Cranwell parade ground. Group Captain Worstall, under sentence of a foreseeable posting, could not take on the chairmanship, but Group Captain D. McL. Ferrier was elected to carry on the job so well initiated by Group Captain Worstall. The Honorary Secretary is Flight Lieutenant D. J. Cockrell.

The Graduates' and Students' Reception and Dance, held at Hamilton Place on 31st October, was a very successful affair, with an attendance of over a hundred. The President and Mrs. Dowty, Mr. and Mrs. S. Scott-Hall and Mr. and Mrs. N. J. Hancock enjoyed the party also. Mr. D. C. Smith introduced square-dancing and the performance was acceptable. It was held on Hallowe'en, but there was no "dookin" for apples. Perhaps another year!

In addition to Merthyr Tydfil and Henlow, I have visited Weybridge and Halton. At the latter, I heard a paper on High Speed Flight by Corporal Apprentice Jones. It was well done; the lecturer had, to me, a surprising amount of aplomb, although I must say it was disconcerting to be informed that the sines and cosines of an angle did not matter for they were only things taught in a class room!

At Weybridge Sir Roy Fedden gave the first Rex Pierson Memorial Lecture. This was a Main Society Lecture with the President in the chair. There were over 300 present, a tribute both to Rex Pierson and to Sir Roy. To plagiarise—"The amount of top brass" was quite phenomenal. It was heartily agreed that this series of Lectures could not have been initiated in a better manner.

The Lecture was followed by a Dinner, given by Vickers-Armstrongs to commemorate the occasion. The speakers were all friends of R.K.P., and each paid his personal tribute.

The whole conception of the evening was good, and the result was an excellent piece of organisation. My congratulations to the Weybridge Branch, President, Chairman and Secretary, and all the others concerned.

On 14th November, at the invitation of Scottish Aviation, I visited Prestwick to attend the Twelfth Anniversary Dinner of Trans-Atlantic Air Services to Prestwick Airport. The Minister of Civil Aviation and Transport was the Guest of Honour, and replied to the toast of the Guests. The pawky humour of the Provost of Prestwick delighted his hearers, when he spoke on absent friends.

The First Branch Area Meeting was held on Wednesday 19th November at the Queen's Road Hall, Coventry; the lecturer was Mr. R. Hafner, Chief Designer, Helicopter Department, Bristol Aeroplane Co. Ltd. Mr. Hafner spoke on Helicopters, and, at the end, appreciation was expressed of the way he had treated his subject, making the complexities most intelligible to the uninitiated.

Among the Branches represented, in addition to Coventry, were Birmingham, Cheltenham, Bristol and Derby.

The lecture was preceded by a Dinner given by Mr. J. J. Parkes, Chairman and Managing Director, Alvis Ltd.

During the afternoon, before the lecture, I visited Armstrong Whitworth Aircraft Ltd. at Baginton, and was shown over the works by Mr. Dixie Keen, the Assistant Chief Designer.

On the following day, in company with the President, I crossed over to the Isle of Wight, to attend the Annual Dinner of the Branch there. Mr. H. Knowler, in the absence of Sir Arthur Gouge, was in the Chair at the Dinner, and toasts were proposed by Mr. M. J. Brennan and Captain E. D. Clarke, proposing "The Society" and "The Guests" respectively. The replies were given by Mr. G. H. Dowty and Sir Alliott Verdon-Roe.

After the official speeches Mr. Knowler called upon Captain Pritchard and myself to say a few words. Captain Pritchard illustrated with stories the problems of education. Personally, I was pleased to learn that a Bishop could be mistaken—admittedly with malice—for a lady.

After returning to London, accompanied by Mrs. Ballantyne I went to Simpsons in the Strand to attend the second Annual Dinner of the de Havilland Technical School Old Boys' Association, of which Mr. F. T. Meacock, of "The Aeroplane," is the Chairman. This is a very friendly affair, for there are no set speeches. Mr. R. E. Hardingham, Secretary and Chief Executive of the Air Registration Board, told old tales of de Havillands; I merely told old tales.

Accompanying invitations to functions I have received an addendum to the effect that "you will be asked to sing for your supper." One fine day I shall interpret that literally.

Throughout the month I have received a number of interesting visitors, among whom were Mr. Ian Fleming, of the Australian Division, Dr. R. Cheetham, Vice-President of the Southern Africa Division, and Mr. D. B. Lindsay, of the Hong Kong Engineering Co. Ltd.

A. M. Ballantyne

Secretary

NOTICES

CHRISTMAS 1952

The President, Mr. George H. Dowty, the Council and the Staff of the Society wish all members, at home and overseas, a Merry Christmas.

CHRISTMAS HOLIDAYS

The Library and Offices of the Society will be closed from 5 p.m. on Wednesday 24th December until Monday 29th December at 9 a.m.

CONTENTS OF DECEMBER JOURNAL

Problems of Servicing and Reliability, Group Captain G. M. Buxton, O.B.E.
The Design and Construction of Airfield Pavements, M. J. Tomlinson, A.M.I.C.E., A.M.I.Struct.E.
Oscillatory Occurrences in Ball Bearings, Dr. M. S. Frenkel.
Correspondence. Reviews Additions to the Library.
Index to Volume 56, 1952.

An annual sum of £250 is available for premium awards for papers published in the Journal. These premium awards are usually 15 guineas each. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics.

THE AERONAUTICAL QUARTERLY—VOLUME IV

Part I, Volume IV of The Aeronautical Quarterly is available from the offices of the Society at 7s. 9d. (including postage) per copy to members, or 10s. 3d. (including postage) to non-members.

The Contents of Part I, Volume IV are:—

The Initiation and Propagation of Fatigue Cracks in Mild Steel Pieces of Square Section	H. L. Cox and J. E. Field
The Sensitivity and Range Required in a Toepler Schlieren Apparatus for Photography of High-Speed Air Flow ...	W. A. Mair
Note on Mr. Mair's Paper	D. W. Holder and R. J. North
On the Conditions under which Energy can be Extracted from an Air Stream by an Oscillating Aerofoil	N. C. Lambourne
Aerofoil Theory for Swallow Tail Wings of Small Aspect Ratio	A. Robinson
Correlation Between some Stability Problems for Orthotropic and Isotropic Plates under Bi-Axial and Uni-Axial Direct Stress	W. H. Wittrick
The Dust Problem in Hot-Wire Anemometry	D. C. Collis

Members are reminded that Parts 2 to 4 of Volume IV will be published at intervals of approximately six months and that the cost of a subscription (4 Parts) is £1 11s. 0d. (including postage) to members. The subscription to others than members of the Society is £2 1s. 0d., including postage.

Copies of Volumes I, II and III are still available at these prices.

FOURTH ANGLO-AMERICAN AERONAUTICAL CONFERENCE

The Fourth Anglo-American Aeronautical Conference will be held in London from 14th-17th September 1953 under the auspices of the Royal Aeronautical Society and the Institute of the Aeronautical Sciences. Further details will be issued shortly.

Members interested should note these dates. It will be remembered that it was decided originally that these Conferences should be held alternately in the United Kingdom and the United States of America, and normally this Conference would be held in the U.S.A.; but because of difficulties in fixing suitable dates in America it has been agreed to hold the 1953 Conference in London.

DIARY

LONDON

December 16th.
GRADUATES' AND STUDENTS' SECTION. An Introduction to Aircraft Vibration. D. J. Mead. 4 Hamilton Place, W.1. 7.30 p.m.

December 18th.—**POSTPONED UNTIL MARCH** (*see* separate notice on p. 865).
A FULL DAY DISCUSSION ON FATIGUE.

1953

January 29th.
MAIN LECTURE. Titanium. Major P. L. Teed. Institution of Mechanical Engineers, Storey's Gate, S.W.1. 6 p.m. Tea 5.30 p.m.

February 17th.
SECTION LECTURE. Recent Developments in Gliding. A. H. Yates. 4 Hamilton Place, W.1. 7 p.m.

February 26th.
MAIN LECTURE. New Materials and Methods for Aircraft Structure. H. J. Pollard. Institution of Mechanical Engineers, Storey's Gate, S.W.1. 6 p.m. Tea 5.30 p.m.

NOTE: A complete lecture programme for the Spring Session of 1953 will be available in January 1953.

BRANCHES

December 10th.
Brough—Aircraft Propulsion. Professor A. D. Baxter. Electricity Showrooms, Ferensway, Hull. 7.30 p.m. Admission by ticket only.
Reading and District—Industrial Design and the Engineer. K. Brookfield. Abbey Gateway Room, Abbott's Walk. 7.45 p.m.
Southampton—Film evening. Institute of Education, University of Southampton. 7 p.m.

December 11th.
Isle of Wight—Annual General Meeting, followed by a Film Show. Saunders-Roe Sports and Social Club. 6 p.m.

December 12th.
Birmingham—Guided Missiles. W. H. Stephens. Birmingham Chamber of Commerce. 7.15 p.m.
Bristol—Engineering Associations' Joint Dance. The Royal Hotel. 7.30 p.m.

December 16th.
Belfast—Lecturettes. New Hall, Kensington Hotel, College Square East, Belfast. 7 p.m.
Bristol—Presidential Lecture: Design for Production. Dr. A. E. Russell. The Conference Room, Filton House. 6 p.m.
Glasgow—Lecturettes. Royal Technical College. 7.30 p.m.

December 17th.
Weybridge—Fatigue—What it is and Some Ways of Reducing its Incidence. Major P. L. Teed. Vickers-Armstrongs Ltd., Weybridge Works. 6 p.m.

December 18th.
Portsmouth—Films. The Technical School of the de Havilland Aircraft Co. (Portsmouth) Ltd., The Airport, Portsmouth. 6 p.m.

December 19th.
Weybridge—Annual Dance. St. George's Hill Tennis Club.
Coventry—Film evening. Wine Lodge. 7.30 p.m.

1953

January 5th.
Derby—Annual General Meeting. Branch Prize "Ten-Minute" Papers. Rolls-Royce Welfare Hall, Nightingale Road. 6.15 p.m.
Halton—Film Night. Ships With Wings. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

January 7th.
Chester—Aircraft Accident Investigation. Air Commodore Sir Vernon Brown, C.B., O.B.E. Grosvenor Hotel. 7.30 p.m.

January 12th.
Halton—Branch Night. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

January 14th.
Southampton—Annual General Meeting and Film Show. Institute of Education, University of Southampton. 7 p.m.
Weybridge—Reinforced Plastics in Aircraft Industry. G. C. Hulbert, B.Sc. Vickers-Armstrongs Ltd., Weybridge Works. 6 p.m.
Brough—Can We Reach Mars? E. Burgess. Lecture Hall, Electricity Showrooms, Ferensway, Hull. 7.30 p.m.

January 15th.
Isle of Wight—Modern Aircraft Materials. Dr. H. Sutton. Club House, Saunders-Roe Sports and Social Club, Church Path. E. Cowes. 6 p.m.
Portsmouth—Films. Technical School of the de Havilland Aircraft Co. (Portsmouth) Ltd. The Airport, Portsmouth. 6 p.m.

January 19th
Halton—The Art of Detecting and Investigating Faults in the Metallic Parts of the Aeroplane Structure. Dr. J. Fox. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

January 20th
Glasgow—Some Problems and Prospects of Civil Transport. P. G. Masefield. Royal Technical College. 7.30 p.m.
Belfast—British Carriers in Korea. Capt. A. S. Bolt, D.S.O., D.S.C., R.N. New Hall, Kensington Hotel, College Square East, Belfast. 7 p.m.

January 21st
Leicester—Annual General Meeting and Films. The Lecture Theatre, College of Technology, Leicester. 7.15 p.m.
Reading and District—Aircraft Propulsion and Interplanetary Flight. A. V. Cleaver. The Abbey Gateway, Abbotts Walk. 7.45 p.m.
Coventry—Instrumentation for Testing Aircraft and Aero Engines. C. N. Jacques. Wine Lodge. 7.30 p.m.
Halton—*Visit* to K. & L. Steelfounders & Engineers Ltd., Letchworth.

January 26th
Halton—Junior Members Night. Informal talk by Squadron Leader A. E. Druett. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

January 29th
Portsmouth—Production Research in Aircraft. L. E. Bunnett. The de Havilland Aircraft Co. (Portsmouth) Ltd., The Airport, Portsmouth. 6 p.m.

POSTPONEMENT OF ALL-DAY DISCUSSION ON "FATIGUE"

The discussion on "Fatigue" arranged for 18th December has been postponed until some time in March 1953.

Full particulars will be announced as soon as possible.

AWARD OF THE DANIEL GUGGENHEIM MEDAL FOR 1952

Sir Geoffrey de Havilland (*Fellow*) has been awarded the Daniel Guggenheim Medal for 1952. The award has been made for "forty years of pioneering in military and commercial aircraft and the development of long range jet transport."

SIXTEENTH WRIGHT BROTHERS LECTURE

Mr. William Littlewood will deliver the 16th Wright Brothers Lecture on 17th December at the U.S. Chamber of Commerce Building Auditorium in Washington D.C. His subject will be "Technical Trends in Air Transportation."

JUNIOR INSTITUTION OF ENGINEERS

Air Commodore F. R. Banks (*Fellow*) was re-elected President of the Junior Institution of Engineers in September 1952 for a further session. He will give his Presidential Address on 12th December 1952 on "The Air and the Future" at the Royal Society of Arts at 7.30 p.m. Members of the Society who wish to attend should apply for tickets to the Secretary of the Institution, 39 Victoria Street, S.W.1.

ASSOCIATE FELLOWSHIP EXAMINATION—DECEMBER 1952

The next Associate Fellowship Examination will be held on 15th, 16th and 17th December 1952 in the offices of the Society. The Library will be closed to members on those days. All candidates have been sent a timetable and full particulars of the examination.

SIXTH LOUIS BLERIOT LECTURE 1953

The Sixth Louis Bleriot Lecture will be given by General Guy du Merle (*Fellow*) in London at the Institution of Mechanical Engineers, Storey's Gate, S.W.1, on Thursday 19th March 1953. The title of the Lecture will be "Making Commercial Aircraft Pay."

MEMBERS' NEW APPOINTMENTS

J. W. ADDERLEY (*Associate Fellow*), formerly of A. V. Roe (Canada) Ltd., has joined the Technical Sales staff of the Aircraft Division of the English Electric Co. Ltd.

Dr. J. A. J. BENNETT (*Fellow*), formerly in charge of the Helicopter Branch of the Fairey Aviation Co., has joined Hiller Helicopters of Palo Alto, California, as Assistant to the Chief Engineer.

M. J. BRENNAN (*Associate Fellow*) has been appointed Chief Designer of Saunders-Roe Ltd. in succession to Mr. Henry Knowler (*Fellow*) who remains a Director of the Company. Mr. Brennan was formerly Deputy Chief Designer.

G. F. BRIGINSHAW (*Associate Fellow*) has recently become Sub-Contracts Liaison Engineer at A. V. Roe (Canada) Ltd. (Gas Turbine Division). He was formerly with Rolls-Royce Ltd.

AIR COMMODORE SIR VERNON BROWN (*Fellow*) is retiring from his position as Chief Inspector of Accidents at the Ministry of Civil Aviation on 31st December 1952. Mr. Patrick Tweedie is to succeed him.

A. W. FRASER (*Associate Fellow*), formerly in the Design Office at Bristol Aeroplane Co., has taken up an appointment as a Senior Designer with the de Havilland Aircraft Co. at Hatfield. Mr. Fraser was at one time Honorary Secretary of the Glasgow Branch of the Society.

T. R. GULLSTRAND (*Associate*) has been appointed aeronautical research scientist at S.A.A.B. Aircraft Co., Linköping, Sweden.

I. M. HAMER (*Associate Fellow*) has recently been elected to the Board of Trustees of Dowty Equipment of Canada Ltd., as Technical Director.

E. E. LABRAM (*Graduate*) is taking up an appointment with A. V. Roe (Canada) Ltd.

W. L. MORSE (*Associate Fellow*) has taken up a position as Senior Stress Engineer with A. V. Roe (Canada) Ltd.

WING COMMANDER H. PRIESTLEY (*Associate*) has recently been appointed to the command of No. 3620 (County of Norfolk) Fighter Control Unit, Royal Auxiliary Air Force.

P. RIVERS (*Associate Fellow*), formerly of the Fairey Aviation Co. Research Division at Heston, is taking up a post as Development Engineer in the Mechanical Engineering Section of A. V. Roe and Co.

F. H. ROBERTSON (*Associate Fellow*) has joined the staff of Short Bros. and Harland Ltd. at Belfast. He was formerly Chief Project Engineer at Saunders-Roe Ltd.

ANNUAL SUBSCRIPTIONS

Members are reminded that their annual subscriptions become due on 1st January 1953. The rates are:—

	HOME	ABROAD
	£ s. d.	£ s. d.
Fellows	5 5 0	4 4 0
Associate Fellows	4 4 0	3 3 0
*Associates	3 3 0	3 3 0
Graduates (aged under 26) ...	2 2 0	2 2 0
Graduates (aged 26 and over) ...	2 12 6	2 12 6
Students (aged under 21)	1 1 0	1 1 0
Students (aged 21 and over) ...	1 11 6	1 11 6
Companions	3 3 0	3 3 0
Founder Members	2 2 0	2 2 0

*Any Associate elected before 1st October 1947 may, if he wishes, elect not to receive the JOURNAL, and in this case his subscription will be reduced by £1 1s. 0d. to £2 2s. 0d.

It will avoid delay and confusion if members, when sending remittances for subscriptions, will state their names clearly and give their addresses and grades of membership. Remittances should be made payable to the Royal Aeronautical Society.

ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Benjamin James Allen (*from Graduate*)
Reginald Albert Lloyd Arkell (*from Graduate*)
John Boshar
Fred Brookes (*from Associate*)
Richard Peter Castle (*from Graduate*)
Alexander Craig
Patrick Lawrence Crowell (*from Associate*)
Ernest Charles Garrard
Ivon William Graham (*from Graduate*)
Leonard Desmond Gurney (*from Graduate*)
William James Hemphill
Harold Frederick Hawkins (*from Graduate*)
Arthur Vernon Hawley (*from Graduate*)
William McKim
Alec Measures (*from Graduate*)
Christopher Lawrence Paice (*from Graduate*)
Geoffrey Ratcliffe (*from Graduate*)
Robert George Reed (*from Graduate*)
Kenneth David John Ross (*from Graduate*)
Oliver Stafford Smart (*from Associate*)
Barry Trevor Turner
Thomas Turner

Associates

Joseph Charles Brandt
Leslie John Chandler
George Arthur Vere Clayton
David Charles Collins
Wilson Carruthers Forster
John Evan Griffiths
William Edward Dennis Makin
Edwin Henry John Pallett
Albert George Payne
Thomas Edward Henry Rickard
George Charles Stickland
Ronald Coates Smith
Norman Ralph Taylor
Wilfred George Toogood
Leslie William Warren
Ronald Edwin Watts
John Wiseman

Graduates

Anthony Dobson Barber
Kenneth Richard Brine
George Ernest Carr
Graham Arthur Cropper
Ronald Wheeler Cross
Brian Dutton Henshall (*from Student*)
Aly Sadek Lotayef
John Denis Mann
Richard John Margetts (*from Student*)
Kenneth Tudor Owen (*from Student*)
Brian Edward Rayner (*from Student*)

Students

Frederick Anthony Herbert Ashmead
Philip Joseph Coates
Jeremy Patrick Bourne Cuffe
William Morgan Davies
Ebenezer Thomson Denholm
John Laurence Doyle
Peter Guthrie Durrant
John Arthur Knivett
Peter Large
Gabriel Constant Jean Larroucau
John Gordon Scott Norman
John Rudeforth

Companions

Dennis Arnold Clarke
Arvind Narhar Oak

LEVERHULME RESEARCH FELLOWSHIPS 1952

Applications are invited for Fellowships and Grants in aid for research. The Fellowships are limited to British-born subjects and are intended for senior workers who are prevented by routine duties or pressure of other work from carrying out research. Application forms may be obtained from the Secretary, Miss M. Branney, Leverhulme Research Fellowships, 3/5 Salisbury Square, London, E.C.4. Application must be received *on or before 31 December 1952.*

ACKNOWLEDGMENT

The Council acknowledge with thanks the return of back numbers of THE JOURNAL from Commander F. W. N. Bassett, *Associate Fellow*, R. A. Jeffs, Esq., *Student*, and J. C. C. Taylor, Esq., *Associate Fellow*.

ELLIOTT MEMORIAL PRIZE

The Elliott Memorial Prize has been awarded to Aircraft Apprentice J. Robertson of the January 1950 Entry at R.A.F., Halton, who has obtained the highest marks in the General Studies Examination. The prize will be presented at the Graduation Prize Giving on 16th December 1952.

JOURNAL BINDING

Self-Binder Cases

Self-Binder cases of the "Easibind" type are available from the offices of the Society. These binders are for members who do not have their Journals permanently bound, or who wish to keep their Journals together during the year for binding later.

These cases will hold 12 Journals which are kept in place by means of flexible steel wires. Journals can be inserted or withdrawn easily without damage, so preserving the contents for permanent binding later. The Journals will open flat at any page.

The binder is strongly made in durable dark blue leather cloth on stiff board covers and has gold lettering on the spine. The year is not blocked on the spine but there is a panel on which members who wish to use the binder as a permanent case can put the date.

The cost is 11s. 6d. each including postage and packing for either the size to fit 1952 and previous Journals, or for the size to fit the Journal from January 1953 which will be increased in size. Orders and remittances should be sent direct to the Secretary at the offices of the Society and it is important to state whether the old size or new size is required.

Permanent Binding

There is no increase in the price of permanent binding of Journals. The prices are:—

1952 Volume (including packing and postage)	16s. 0d.
Previous Volumes (including packing and postage)	18s. 0d.

Journals, with a note of the name and address of the sender, should be sent direct to the Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the offices of the Society.

CHANGES OF ADDRESS

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars:—

Name (in block letters).
Grade of membership
New address (in block letters).
Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the JOURNAL for the following month.

*Problems of Servicing and Reliability**

by

Group Captain G. M. BUXTON, O.B.E., M.A., A.F.R.Ae.S.

1. INTRODUCTION

There are two parts of this paper, the first dealing with Servicing and the second with Reliability. Although they are connected in many ways, and indeed servicing has been taken to mean checking parts which might be unreliable, it is convenient to separate them.

PART I—SERVICING

2. TREND TOWARDS INACCESSIBLE INSTALLATION

A practical factor of increasing importance is the burial of the accessory machines in modern aeroplanes.

Compared with, say, a plough, the parts of Blériot's Anzani engine might be thought to be dangerously concealed; dangerous, that is to say, if its working depended on any condition of the internal parts which could be judged when looked at. But the Anzani engine was simplicity itself, compared with any modern machine, even an accessory machine, and these machines are usually covered by, or rather entangled in, the structure.

It is impossible to look at these parts often; a long time is needed to get at them, get them off, and take them to pieces, so that this can be done only when the aeroplane is generally overhauled and a number can be taken out and done at the same time. In any case it is often necessary to take out some machines to get at others behind them.

The longer time needed for inspection makes it practically necessary to design the machine to work with less inspection or servicing adjustment, and what must be done, must be quickly done.

3. KNOWLEDGE OF SERVICING

Design for servicing is one of the tricks of the aeroplane designer's trade and new and promising aspirants will be disappointed to hear that it is learnt from experience. It would be very misleading to think that ability to provide this servicing design, therefore, comes slowly; of all things it responds to study and imagination which takes advantage of experience.

The basic point to be imagined by the designer is that servicing is workaday. Even the most experienced man feels a faint sense of relief when his new aeroplane first flies successfully, and until then the provision of design features which must distract his thinking from the main aerodynamic and structural design, to provide good servicing, is a feat of confidence and imagination which must not be underestimated.

The man who is to design a good aeroplane must first realise that it will fly successfully, it will be bought by the Services, and it will have a life in use many times longer than the period of development. Moreover scores, hundreds, and even thousands of such aeroplanes will be built and every one will be used continuously. It will, in fact, be a workaday task to service each one of them and seconds saved in any operation will be multiplied a thousand-fold and in some instances a million-fold.

These facts are familiar to people who are making civil aircraft; with military aircraft, much more is left to the judgment of the designer, but servicing is still important and second only to operational performance.

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*A Lecture given before the Bristol Branch of the Society on 15th October 1952.

Group Captain Buxton is Assistant Director of Servicing Research and Development in the Ministry of Supply and is responsible for the Design for Servicing of Aircraft and for focusing Service requirements for reliability. In 1938 he read before the Society a paper "Development of Sailplanes" for which he was awarded the Edward Busk Memorial Prize.

4. SOME COMICAL EXAMPLES

Even the best firms have made mistakes, and two are quoted here.

A large aircraft was being considered at one of the very large Ministry of Supply meetings and it was found that the battery could not be charged while it was on the bus-bar. It was a 98 volt battery and would have to be removed if in need of recharging.

The R.A.F. has found that a great proportion of the defects of 24 volt batteries is caused by removal and has decided not to remove 98 volt batteries, but to charge them in place; so that they have not provided the equipment for removing this weighty object. It was agreed at a meeting that an arrangement by which the battery need not be removed but could be taken off the bus-bar and connected to the charge truck would do. The proposal involved the idea that the aircraft, which costs about a quarter of a million pounds, should stand on the ground while the battery was being recharged and that meanwhile the internal circuits should be dead and the servicing work and checking necessary on any wireless, radar, bombing, gun circuits, engine control, electric tank switches, and flying instruments should cease! Not a workaday arrangement!

In a still more modern aeroplane, the fuel and water drain cocks for one fuel tank were perfectly accessible to anyone who could reach them when the aeroplane was in flight; unhappily they were completely covered by a fairing panel when the undercarriage was extended!

5. THE PROBLEM OF PANELS

Panels must go on easily and quickly. Often a mechanic has been seen banging a panel into place; if he is working against time and if that treatment is the quickest, the only conclusion is that the designer intended the panel to be treated in that way!

If distorted, panels also affect performance and therefore, on two counts, the effort to achieve a well considered and good design is justified.

6. ENGINE INSTALLATION

Engines are now, unavoidably, encased in a stressed skin structure. But the engine controls must be adjusted and parts inspected.

Access holes may be provided for these purposes but a quantity of them are needed for efficient servicing. A good solution is seen in the Sabre whose engine can be run in place, partly exposed, after the rear fuselage has been taken off. It may be, that all single-engine fighters should be designed to allow this to be done.

7. POWER CONTROLS

At the new speeds and weights power controls are being widely used, and the maintenance engineer must adopt a new policy to cope with them. Those with some experience know of the analogous automatic pilot which purports to be able to control the aeroplane, and which, in fact, implicitly relies on the presence of a human pilot to disconnect it and take over when it fails, which occurs from time to time. Two arrangements are made: in one, called Manual Reversion, there is some direct link between the pilot and the control so that he can hope to operate it, at least at limited speeds, and to have some limited control on the aeroplane by exertion of his utmost strength. If a broken power control does not hinder him, such arrangement has a powerful advantage for safety. In another, an alternative system is brought into use automatically or manually, if the primary system fails.

It is not necessary at this stage to underline the difference between the potential reliability of the mechanical connections used hitherto between the stick and the control service, such as cables and rods, and complex engine-driven or motor-driven miniature hydraulic motors and pumps and electric motors which are used for a power control.

8. HIGH STANDARD OF SERVICING WORK NEEDED

The reliability of these mechanisms is discussed later, but the problem of servicing them needs a clear policy because of the extremely high standard of treatment which they require. Dust, which has never been excluded entirely from other hydraulic systems, must be absolutely excluded; the hydraulic joints which have never otherwise been entirely prevented from leaking must be, with the very small reserves of hydraulic fluid which are provided, entirely leak-proof. The obscure reasons which have caused pick-up and seizure in hydraulic pumps and motors must be solved and causes eliminated, and finally, when every possible action of this kind has been taken, there must be the duplication necessary to ensure at least some

remnant of control power when the set is injured by an enemy bullet.

The extra burden which this imposes on the service, to provide an established permanent system of maintenance, including such things as highly-trained thoroughly-experienced men and air-conditioned dust-free workshops, can be imagined. The whole Middle East Campaign in the Second World War was completed without it being possible to make such arrangements.

The far-sighted engineer will foresee where certain standards of servicing will be impossible to achieve in war, and a mechanism which is designed to work only if such standards are provided must be rejected and redesigned.

* * * *

The problem of reliability is explicitly, or implicitly, settled in all machines and it is necessary only to look at the particular influences that bear on aeroplanes, and service aeroplanes in particular.

PART II—RELIABILITY

9. THE PRELIMINARY VIEW

In the Blériot, the simple airframe parts could be inspected for wear, so that servicing inspection was a contribution to reliability, besides having the normal function of replenishment, oiling and cleaning.

The engine was too complex for frequent dismantling and so could not be inspected, and the type test was adopted in early days as a test of reliability for a given life.

In modern aircraft, many machines are too complex for frequent inspection, and several items, of which the radio valve is the extreme example, cannot be inspected for reliability or freedom from fatigue. In all such parts, reliability is needed as an intrinsic quality.

10. EFFECT OF THE NUMBER OF PARTS

According to the statisticians, the most probable reliability of the set is the product of the reliability of the components. For example, with one hundred components, each of which was expected to fail once in one hundred sorties, and assuming that it had in fact failed once in the one hundred sorties, there are a number of possible results. The extreme results are that, either one failure occurs on each sortie so that no single sortie is completed without a failure, or that all the failure occurred in one disastrous sortie, the other ninety-nine being done without a failure at all. In a discussion an ingenious disputant will probably suggest that such cases might occur. This is true, but in fact, their occurrence is improbable; the chances against the former case, where there is a defect on every sortie, is $10^{47} : 1$ and the chances of the latter case, where all the defects occur on one sortie are $10^{200} : 1$. The most probable arrangement is that the reliability of the collection of components would be $(0.99)^{100}$ which is 36 per cent. and there would probably be enough items (100) to make an actual experience approximate to this figure.

An engineer is accustomed to work for definite and certain results, but it is necessary to follow statistical theory in questions of reliability. No certainty results from this, but only probability, *i.e.* a chance that any given standard of reliability will be achieved; the statisticians often suppose that the result is "significant" when the chance is 20 :1.

The mechanical engineer is accustomed to the kind of mechanical defect which can often be cured by local re-design: but with greater complication, and with such things as electronic sets, even an improvement may have to be stated as a probability. With complex sets comprising parts with a known incidence of failures, the multiplication of the parts causes a corresponding calculable decrease in reliability of the set. Or, if this reliability is to be maintained, the reliability of the parts must be correspondingly increased. Fig. 1 has been drawn to show this relationship for the special case of a number of similar essential parts in a set, *e.g.* valves in a radio set. It shows the degree of reliability in the parts and the corresponding reliability of the set.

The word reliability is used here to mean the number surviving an occurrence, *e.g.* if 92 per cent. of the radio sets worked throughout a sortie, the reliability would be 92 per cent., and the failure rate 8 per cent.

It is a severe problem, for a failure rate of 0.01 per cent. is high enough. But then, parts are usually made by men, and if, by analogy, the reliability is compared of, say, a business man catching his morning train, a failure rate of 0.01 per cent. is found to be equivalent to missing the train about once in thirty years!

11. DISTRIBUTION OF FAILURE RATE

One careful analysis made of all the failures of an aeroplane which has been in operational use for some years covers a sample of several thousand sorties.

Figure 2 shows the items which had defects as abscissa, and the number of defects per item as ordinate, and it can be seen from the figure that the repeated failures in six items caused 40 per cent. of all the failures, while two hundred items failed from one to four times and caused 20 per cent. of the total.

12. PREVENTION OF SLIGHTLY UNRELIABLE PARTS

For reasons of expense, only the more troublesome parts can be modified, but the rarer defects can be prevented by better design or manufacture or, alternatively, by more thorough life-testing of the part. It is fortunate that such life-testing may also discover the weaknesses of the items which fail repeatedly.

Every engineer of experience agrees that reliability testing is needed, but there is, naturally enough, too little experience. For example, a Ministry official at a firm asked whether the R.A.F. realised that hydraulics must not be opened up for replenishment or inspection during a sandstorm! He had no idea of conditions in the Western Desert.

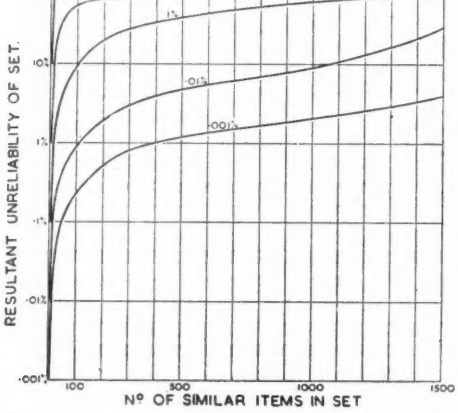


Fig. 1.—Quantity and reliability. Most likely unreliability of a set of identical parts.

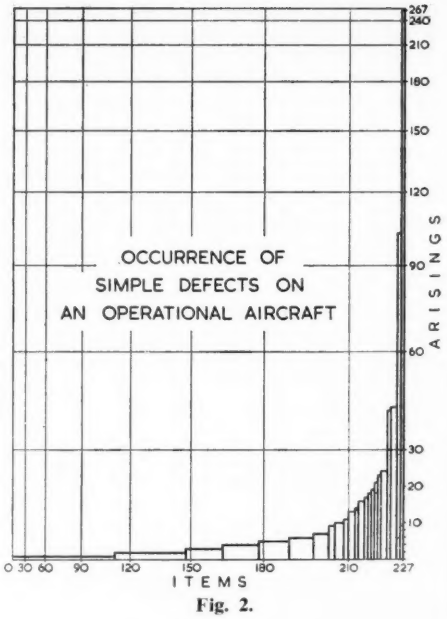


Fig. 2.

Those who were there remember places where there was a continuous sand haze. The food tasted of grit at breakfast, lunch, tea, and supper and there was a layer of sand on the pillow at night. The human machine continued to work fairly well, but flying machines were inclined to fail.

Many engines wore out on their delivery flight. Few lasted for more than 1/10 or 1/5 of their normal lives. It was months or years before intake filters were fitted. The engines of some aircraft wore out on the delivery flight across Africa, before they ever got to the war. The Wright Aeronautical Corporation at that time, it is believed, laid down that the oil consumption of the Cyclone engine should be not more than 6 pints an hour; when collecting such aircraft from the supply route for repair, they had to be flown, as there was no ground transport, and there was a local rule that these engines could be flown if the oil consumption were not more than 6 gallons an hour.

But we should remember our state of mind at that time before it can be confidently assumed that we are wiser now than we were. While a number of parts undergo tests of their reliability, and specifications in some fields lay down realistic and effective test

conditions, it is still true that a quantity of components are not run under severe working conditions for a working life before being adopted for production, nor are early production models invariably checked. And when such tests are proposed, there are still those who can think of reasons, often superficially convincing, why they should not be done.

13. USE OF ACCUMULATED EXPERIENCE

Rare failures do not appear until many hours of flying have elapsed and the frequency of their recurrence cannot be assessed until many times this period has passed; so that a purely statistical approach to the estimation of their importance is either very expensive or very slow. But accumulated engineering experience can be used as a substitute for a rigorous statistical method and a suitable engineer can judge from the first case the likelihood of its repetition. It is necessary to take care that this judgment is made with common sense or is statistically sound, which may be taken to be the same thing! The engineer must be experienced enough to investigate the effects of unusual environment, the possibility of maltreatment or misuse, and possibly of a remote random and rare effect having caused the failure, but with these provisos he can often give an immediate diagnosis of the likelihood of repeated failure from a study of the first failure.

14. MEASUREMENT OF RELIABILITY

It is one of the most prominent activities of aeronautical engineers to measure performance which, *ipso facto*, leads to its preferment, but reliability hitherto has not been measured or reported, in spite of its importance. It must be accepted for the present that it is impossible to treat every failure as a disaster, to be eliminated at any cost, and that the problem of reliability must be improved in engineering terms, namely, after measurement. This is the necessary preliminary to considering the reliability in any way, to assessing its cost, and to the direction of attention to its improvement, which naturally should be done by concentrating on the most troublesome and costly items.

Moreover, the measurement of reliability has an impartial effect in showing the loss of striking power due to failure. Part of the difficulty of dealing with reliability has been that the real cost of an aeroplane standing on the ground, together with the loss of usage of the aerodrome, hangars, runways, supervising personnel, staff, and so on, does not appear in any accounting.

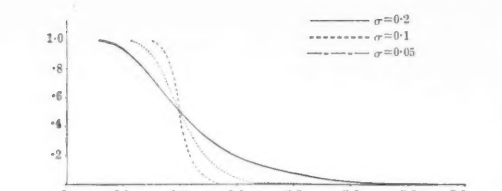
One of the most interesting things in this study is the range of types of reliability. It begins with the simple mechanical bearing or similar piece where, provided that adequate strength and stiffness is present in the design, the reliability will depend on regular servicing, in the form of lubrication and regular inspection of the wear of the part, so that it can be changed before it wears out.

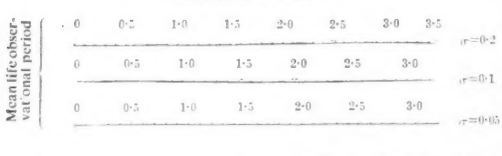
15. THE RADIO VALVE

The radio valve is interesting because it represents the other extreme. This is an item which is uninspectable in use, and so the degree of reliability must be present when it is first issued to the Service, and the continuance of reliability depends only on freedom from misuse, including shock and electrical overloading, and perhaps time.

It is rather curious that the effect of time, that is length of life in use, is not yet known and discussion still rages around this problem. Would it be a good thing, for example, to " age " a valve by giving it a run before it is put into service? This run to be in full simulated Service conditions such as vibration, temperature, and perhaps even altitude, or would this rather expensive provision be unnecessary? Where the valves have an initial high rate of failure, reduced by such treatment or not, does the rate of failure increase rapidly after a certain life and would it be desirable therefore to reject valves before they fail? Or does the valve become more reliable with life, so that the older the valve is the better?

The degree of importance of this subject alone warrants mention. The number of valves in a modern bomber is now thirty times as many as in a bomber in 1939 and any knowledge of recent operational theory will show that the importance of their functions has increased in a similar way. Moreover, there is information from both military and civil authorities in the United States, where more technical effort has been given to the study of the problem than here, that about half of the failures experienced are





Courtesy of Boulton Paul Aircraft Ltd.

Fig. 3.—Probability of an occurrence when there is a mean life.

caused by failures of valves. As the valve must be exceedingly reliable, the observation to discover average failure rates is a long and expensive job.

16. THE BASIC CRITERION

A good test will cause defects to show which would otherwise be found in service. In practice, when parts fail on test, they should be redesigned before use. But it is important to remember that the test must be realistic, and it is a good sign of the competence of an engineer that he can design workshop tests which have a real meaning.

The basic criterion of reliability is the behaviour in use. The use must be typical of wartime, and the records must be accurate; but all designing and testing can be confirmed only by successful operation.

At this point the work of Boulton Paul Aircraft Ltd., who have a contract to investigate design for reliability, must be mentioned. It is to be hoped that the Society will hear a full account of their original and interesting work; the argument that follows here was developed by them.

17. REPLACEMENT LIFE

Replacement is an important question in any maintenance organisation. What life can be given to various parts, and should they be replaced at a given life, before they fail, in order to maintain reliability? According to the paper "Aircraft Servicing" in the November 1948 JOURNAL, by Norman and Wilkinson, it seems that they should.

If so, it is first necessary to decide on the life, for this decides how much of the useful life of the parts that would have lasted is wasted by throwing away, and what chance of failure remains in the accepted useful life.

Figure 3 assumes that the ratio of the resistance to use (or "usage worthiness") and the severity of use are analogous to a cyclic stress, and that the log of the life is proportional to this stress. If the stress is normally distributed (Gaussian) the lives will have a dispersion dependent on the standard deviation of the stress.

The figure shows the probability of a defect happening in time, in terms of the mean life. As a standard deviation of 0.2 may perhaps be expected, the difficulty in estimating a working life is considerable or rather, the loss of use involved in adopting a "throw away" life that is safe may be rather high. For example, in a discussion with a U.S. airline on the engine rear cover, which was prone to cracks, the suggestion that it could be discarded before failure (instead of being inspected and used) was said to be too costly, for the life of one was often many times the life of another. Other defects, for example gun stoppages, appear to have a random occurrence without correlation with life.

18. RESPONSIBILITY

In investigating the causes of defects, one of the main objects is to find out who is responsible for them. The contractor has bravely tried to analyse 1,615 defects. Such an analysis may be the basis of a general improvement but it is particular, and only applies accurately when all conditions, *i.e.* the men, maintenance system, aircraft type, usage, and so on, are unchanged. In this instance it was found that the maker and the user were responsible for nearly equal numbers of defects!

19. MEASURES OF THE EFFECTS

In measuring defects, the mere fact of the occurrence of the defect may be important or not, and there are three possible measures, first, the effect on "operationworthiness"; secondly, the length of time the aircraft is out of action as a result; thirdly, the labour, in "man hours," to rectify.

The object and end of the work of the Services is war operations, but these operations are themselves complex so that they cannot be used as a measure; moreover they

do not occur in peace time when much of the engineering work of the Services is done. The second measure, the length of time the aircraft is unserviceable, is easier to use, although even here there is room for the exercise of judgment; aeroplanes often suffer from more than one defect, and the time of unserviceability may be affected by the efficiency of the organisation. The last criterion is very useful for all questions of engineering economics but may have little direct relation to the operational loss caused by unreliability.

Any system of analysis must watch these measures, but the simple criterion of number of defects may still be the most useful measure. It is simple, easy to define, and so likely to be accurate. Moreover every defect carries with it such an overhead cost, in the fact that it has cancelled a plan and made an aeroplane unserviceable, that there is significance in its very occurrence.

The operational aircraft can be supposed to be an entirely functional device, which has no ornament or amenity and which will lose some of its fighting value if any of its parts fail to work. In fact, the striking power of the Royal Navy Air Arm and the Royal Air Force depends on the intrinsic reliability of all parts.

20. FUTURE ANALYSIS

The body of the work is still to come; all the data from observations have been transferred to punched cards so that the power of a mechanical sorting system can be used for comparative analysis. Fig. 4 shows a selective analysis, as an example of this work.

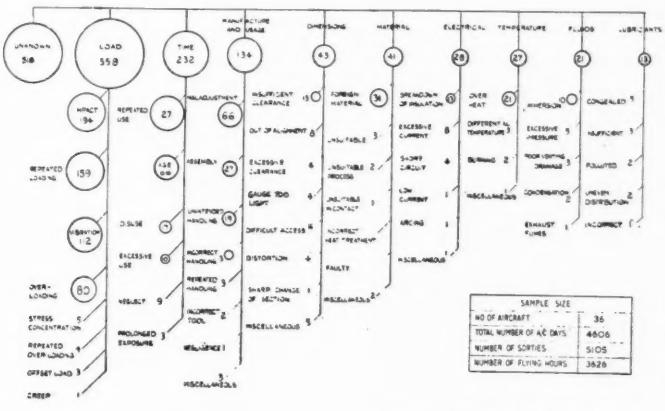
The lesson to be drawn is that the problem of reliability is difficult because of the low-geared nature of the events. It takes a great and expensive effort to produce an aeroplane flying hour, and it takes an enormous number of flying hours before even a part which is only moderately reliable will fail. The number of parts in the aeroplane is so great, unfortunately, that failures of some part of the aeroplane are all too frequent. Progress has brought forward the old difficulty in an aggravated form, and the observation and analysis must be more systematic and thorough to match it. The finding of the responsibility for failure or, in view of the satisfactory performance of individual parts, the finding of the man who can improve the part, becomes possible once it is known what needs improving.

CONCLUSION

Can the needs be stated in brief?

How can design for servicing be improved? Basically, by field experience for the designers and by their sense and imagination working on this experience.

And for reliability? Surely by field experience again in the designer so that he has a basic understanding of the conditions of use for which he is designing. And reciprocally, by good knowledge in the user



Courtesy of Boulton Paul Aircraft Ltd.

Fig. 4.—Cause allocation for all defects. 1615 defects.

of the qualities and characteristics of the machine and how it should be used. The adequacy of the design needs to be checked by a test of reliability, giving the part a working life under severe conditions of service to disclose any weaknesses and so to save the expense of rectification after mass supply, and the greater expense of cancelled and abortive sorties.

The final proof lies in the intensive flying trial which gives the results that only happen under natural working; reliable results depend on the treatment which must be as much like the treatment in war as is possible.

ACKNOWLEDGMENT

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*The Design and Construction of Airfield Pavements**

by

M. J. TOMLINSON, A.M.I.C.E., A.M.I.Struct.E.

1. INTRODUCTION

Before the Second World War there were few airfields in Great Britain with paved runways.

The grassed flight strips of the pre-war years could carry the wheel loads of the aircraft then in use with little maintenance, other than grass cutting and rolling clinker or stone into local soft patches. From 1939 onwards, the increasing weight of aircraft, and more intensive flying, made it necessary to construct airfields with paved runways to permit operation in all weathers.

From 1939 to 1945, 444 airfields were constructed with paved runways for the Royal Air Force at a cost of £200,000,000, excluding the cost of building construction. Since 1945 the emphasis has been upon airfields for civil use, and the great airfields at Idlewild, Boston, Johannesburg and London Airport have been built. The peak of this civilian construction has now been passed and present work is confined to extensions and improvements to existing major airports to cope with greatly increasing traffic, and the bringing into service of new and heavier transport aircraft. The emphasis is once again being transferred to military purposes.

The design and construction of airfields falls within the province of the civil engineer.

The great increase in aircraft weight in the past ten to fifteen years has led the civil engineer to believe that the aeronautical engineer is not bound by any inhibition of weight and size. The naval architect does not design ships that are too large to enter the harbours or dry docks in the seaports of the world. Yet five years ago there were several types of aircraft under construction that were far too heavy for nearly every airfield runway in the world. In recent years aeronautical engineers have come to realise the practical limitations in the length and thickness of airfield runways, and have developed multi-wheel undercarriages which greatly relieve the intensity of loading on the paving.

This paper describes the various factors which influence the layout and design of airfield pavings, and emphasises the important effects of wheel load, wheel spacing, and tyre pressure on the designed thickness.

The thickness of paving has a very powerful influence on the overall cost of an airfield. The standard heavy-bomber airfield has about 1,000,000 yd.^{2} of paving, and at London Airport 4,500,000 yd.^{2} have already been laid, with the project still incomplete. A saving of one inch in thickness can mean a saving of about £150,000 in one million square yards of concrete, which emphasises the care that the civil engineer must take in designing the pavements to carry the loadings imposed upon them by the aircraft designer.

2. LOCATION OF THE AIRFIELD

The problems of airfield location vary widely and depend almost entirely on the use to which the airfield is put. For example, the siting of military airfields depends solely on strategic considerations. They are usually in areas as far as possible from large towns and, unless they are in mountainous country, their siting does not present any difficult problem.

The selection of suitable sites for civil airports is likely to be more difficult. It is essential that they should be as close as possible to large centres of population, but at the same time the direction of the prevailing wind should not be such as to blow

*Lecture read to the Birmingham Branch of the Royal Aeronautical Society at Wolverhampton on 7th December 1951, when slides showing the various stages of airfield construction were shown, in addition to the figures included here.

Mr. Tomlinson is with George Wimpey & Co. Ltd.

smoke and industrial haze over the airport. If possible, the approach to the main runway into the prevailing wind should not be made over large towns.

With these severe limitations in location it is often difficult to find a suitable level site free from industrial or housing development at a reasonably close distance to the city being served. For this reason the airport engineer is often forced to pick a site which for one reason or another has been rejected as unsuitable for building development. He may have to construct his airport in a swamp, or a low-lying area in a river estuary liable to periodical flooding. For example, the international airports at New York and Boston are on areas reclaimed from the sea shore. The main airport at Kallang in Singapore is on reclaimed land, while the site of London Airport was covered by old gravel pits.

3. LAYOUT

Airfield layout varies with the use of the field, the traffic intensity, the prevailing winds, and the physical features of the site. For military airfields a simple triangular runway pattern with a perimeter track connecting the ends of the runways was developed during the 1939-45 War. The main runway was in the direction of the prevailing wind, and the other two runways were at an angle of about 60° to the main runway. Hardstandings were grouped around the perimeter track, and hangars and administration buildings in an area between the ends of two diverging runways.

The layout of civil airports is more complex, since high traffic intensities have to be dealt with and there must be facilities for rapid handling of large numbers of passengers at a single terminal area. To meet these requirements there are a number of elaborate layout patterns, such as the "catherine wheel" system where a number of diverging runways are sited tangentially to a central terminal area, and the triangular system of dual parallel runways, used at London Airport.

4. DIMENSIONS OF RUNWAYS

The runway length depends on the type of aircraft and its all-up weight, and the height of the airfield above sea level.

The usual requirement for length of runways is that an aircraft should be able to take off, rise to 50 ft., and then make an accelerate-stop manoeuvre with the aircraft coming to rest again on the runway, it being assumed that an engine fails at a point during the ground run.

Suitable main runway lengths are:—

Very heavy transport aircraft or very heavy bombers —3,000 yd.
Heavy transport or bomber aircraft —2,000 yd.
Medium transport or bomber aircraft —1,500 yd.
Light aircraft — 600 yd. or less

A width of 150 ft. is suitable, but major airports usually have runways at least 200 ft. wide. The flight strip, which must be free of all standing obstruction, is usually 200 yd. wide, or 400 yd. for the main runway. The approaches should be free of all obstructions above an angle of 1 in 50 to the horizontal from the end of the runway strip, for the main runway strip. The normal width for taxi tracks is 50 ft., but on major airfields they are 100 ft. wide. Gradients of the runways should not be more than 1 in 80, or preferably 1 in 100.

TABLE I.

Type of Airport	*I.C.A.O. classification*	*Pavement must withstand maximum expected frequency of traffic of aircraft imposing single isolated wheel load of the weight shown below (lb.)*	*The pressures to be associated with loads given in previous column for purposes of design (lb./in.²)*
Inter-continental express	1	100,000	120
Inter-continental	2	75,000	100
Continental	3	60,000	100
Inter-city express	4	45,000	100
Inter-city	5	30,000	85
Feeder services	6	15,000	70
Light services	7	5,000	35

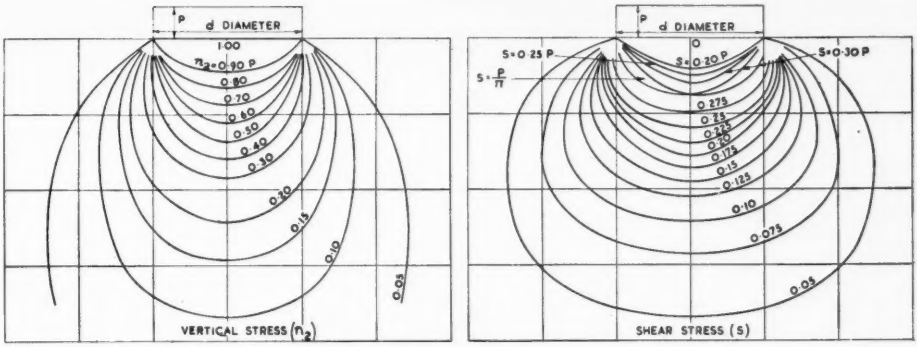


Fig. 1.—Distribution of stresses under circular footing.

5. PAVEMENT DESIGN

In this problem, the civil engineer has the closest link with the aircraft designer.

Pavement design depends on:—

(*a*) All-up weight of aircraft.
(*b*) Number and spacing of wheels in the undercarriage.
(*c*) Impact of wheels.
(*d*) Traffic intensity.
(*e*) Nature and strength characteristics of the subgrade soil.
(*f*) Construction of pavement.
(*g*) Type of surfacing.

These factors are considered in turn.

5.1. AIRCRAFT WEIGHT

The pavement must be capable of carrying with safety the heaviest aircraft likely to use the airfield. For example, an airfield might safely carry Dakotas or Vikings for many years without trouble, but when the airline operator switches to Constellations the runways might break up within a very short time.

Civil airports have therefore been placed in various categories of loading. These categories, established by the Governing International Organisations are shown in Table I. Thus, an airfield designed and constructed to take, for example, continental traffic, cannot be used for aircraft of a heavier load category — except for emergency landings.

Such a classification of airfields is helpful to airline operators in planning new routes. Present-day political unrest often necessitates complete changes of airline routes, and the operator has to know whether the airfields at the intermediate stages can carry the aircraft loadings. Existing airport runways have to be tested to find out whether they are capable of carrying wheel loadings of new types. The usual method is to make repeated plate bearing tests on the pavement at a number of places. The test loads are equal to, or greater than, the intended new loading.

5.2. NUMBER AND SPACING OF WHEELS

The next problem is how the all-up weight of the aircraft is transmitted to the pavement. The greater proportion of the load is carried by the main wheels and, for pavement design purposes, it is assumed that 90 per cent. of the load is so carried.

The shape of the tyre imprint on the pavement surface is roughly elliptical and the average contact pressure is approximately equal to the tyre inflation pressure. The load is distributed by the paving on to the natural ground surface beneath, and sets up shear stresses in the soil, depending on

(*a*) The thickness of the paving,

and (*b*) The rigidity of the paving.

The distribution of the shear stresses through the soil below the runway is normally calculated by the Boussinesq method. Fig. 1 shows the distribution of vertical stress and shear stress at various distances below a circular loaded area at the surface.

Thus the effects of gross load and tyre pressure are related. The magnitude of the maximum shear stress is always the same for equal tyre pressures, but the effect of increasing the wheel load is to increase the

depth to which the maximum shear stress occurs. For a given contact pressure the required quality of the pavement is the same, but as the loads increase the material must be provided to a greater depth in order to keep the shear stress induced in the soil lower than its shear strength.

Increase of contact pressure will require increase in the quality of the paving. For example, a gravel runway might carry aircraft with a 75 lb./in.^{2} tyre pressure, but if the pressure were increased to 150 lb./in.^{2}, a high quality concrete or dense asphalt might be necessary.

Summarising, if wheel loads and tyre pressures are increased, both thicker pavements and higher quality materials are required, but if loads are increased without increase of tyre pressure, then thicker pavements only are needed.

The multi-wheeled undercarriage is a very helpful contribution by the aircraft designer to the airport engineer. It enables a reduction in both wheel load and contact pressure to be made, thus giving a substantial saving in quality and thickness of airfield paving.

Another important development is the track-type undercarriage. This type reduces the contact pressure to the order of 25 to 50 lb./in.^{2} which would permit heavy aircraft to land and take off on lightly surfaced airfields. However, it is believed that the disadvantages are heavier undercarriage weights, increase in length of take off and maintenance problems.

5.3. Impact

When an aircraft is taking off or landing it is travelling fast, and the stresses transmitted through the paving to the soil are of such short duration that deflection of the soil does not take place. Consequently there is not the same risk of distortion and failure of the pavement as there is with static wheel loads, or more particularly when an aircraft is standing with its engines running.

The pavement designer therefore allows the maximum static wheel load, or group wheel load in the central portions of the runways, and makes an increase of 25 per cent. in the safety factor on his design for the taxi tracks, aprons, and ends of runways. This increase in safety factor is intended to cover additional loading caused by vibrations when engines are warmed up, and increases in traffic intensity.

5.4. Traffic Intensity

This has quite an important bearing on pavement design, particularly the intensity of use by the maximum wheel load for which the runways are designed. An airfield frequently used by medium weight aircraft, with only occasional use by heavy aircraft, does not need to have paving as thick as an airfield carrying continuous traffic by heavy machines. The designer takes care of traffic intensity by suitable adjustments to his factors of safety.

5.5. Nature and Strength Characteristics of the Subgrade Soil

It is the subgrade soil which ultimately carries the load, but here the airfield designer has the least choice. Questions of location usually far outweigh any plea from the civil engineer to site the airfield on soil of a good bearing capacity.

5.6. Materials of Construction

Since contact pressure governs the quality of the pavement, for heavy aircraft with high tyre pressures a fairly high degree of flexural strength is demanded.

Engineers divide runway pavement into:—

(*a*) Flexible pavements

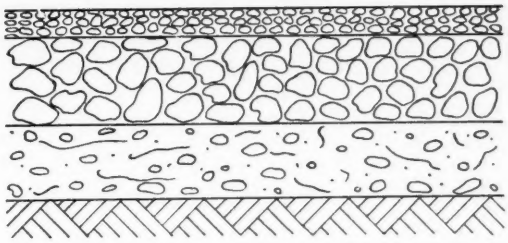
and (*b*) Rigid pavements.

The various courses or components which make up the complete flexible or rigid pavement are shown in Fig. 2.

Flexible pavements consist of a crushed stone or gravel base over which is laid a tarmacadam or asphalt surfacing. Higher mechanical strength is required in the upper layers where shear stresses are high. The lower layers can consist of lower grade materials such as pit gravel or quarry waste.

Rigid pavements are constructed from concrete and, since the extent of distribution of load to the subgrade depends on the flexural rigidity of the concrete slab, it is a general principle that the higher the quality of concrete the less the thickness required.

As an example of the relative thickness of flexible and rigid pavements, a Hermes aircraft with a wheel group load of 37,000 lb. requires a flexible pavement thickness of about 2 ft. for a fairly good sandy clay subsoil, compared with 9 in. for good quality concrete. The choice of method would



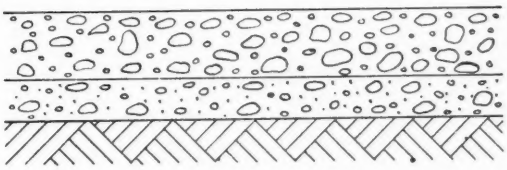
Surfacing (Asphalt or tarmacadam)

Base (Crushed stone or graded sand and gravel)

Sub-base (Quarry waste, sand and gravel, or clinker)

Subgrade (Natural soil)

FLEXIBLE PAVEMENTS



Base (High quality concrete)

Sub-base (Sand and gravel, clinker or lean-mix concrete)

Subgrade (Natural soil)

RIGID PAVEMENTS

Fig. 2.—Components of airfield pavements.

depend on the availability and cost of materials for the two types, and on the amount of excavation or filling required. Where gravel and sand are plentiful the concrete runway is usually cheaper for heavy loadings, but thick concrete pavements require considerable maintenance of joints, and if they crack because of warping, the cost of repairs is high. Present-day interest is tending more to flexible pavings than to concrete, particularly with the prevailing shortage of cement.

5.7. Type of Surfacing

Concrete is a surfacing in itself, and it is understood that pilots prefer the light colouring, especially for night landings. For flexible pavements, some form of durable dust-free surfacing is essential and tarmacadam or asphalt are the main types used. Tarmacadam may deteriorate with age and temperature changes, but asphalt is an exceptionally stable material at any age, and in tropical climatic conditions. Both types of " black-top," as they are called, are liable to softening and disintegration by the spilling of fuel, and blast from jet engines. This is a serious problem, which has not been solved so far. Present-day design allows for concrete surfaced aprons, taxi-ways, and runway ends, with asphalt or tarmacadam paving on the remainder of the runways.

6. PAVEMENT DESIGN METHODS

6.1. Mode of Failure

Failure of an airfield pavement under wheel loading occurs when the shear stresses in the pavement material or the subgrade soil exceed the shear strength of these materials, or when the strains set up by the applied pressures exceed the limiting deflection of the pavement material. When plastic yield or general shear failure occurs, the pavement is deformed and large cracks appear in the surfacing. Water entering the cracks will increase the depth and extent of failure.

Failure can occur in ways other than by aircraft wheel loading. In cold climates, frost heave in a silty soil can completely destroy a pavement unless there is sufficient thickness to insulate the soil from the frost. Some types of soil show marked changes in volume with changes in water content. If the paving is laid in the summer over a dry soil, it is liable to upheaval if the winter rains are allowed to percolate through fine

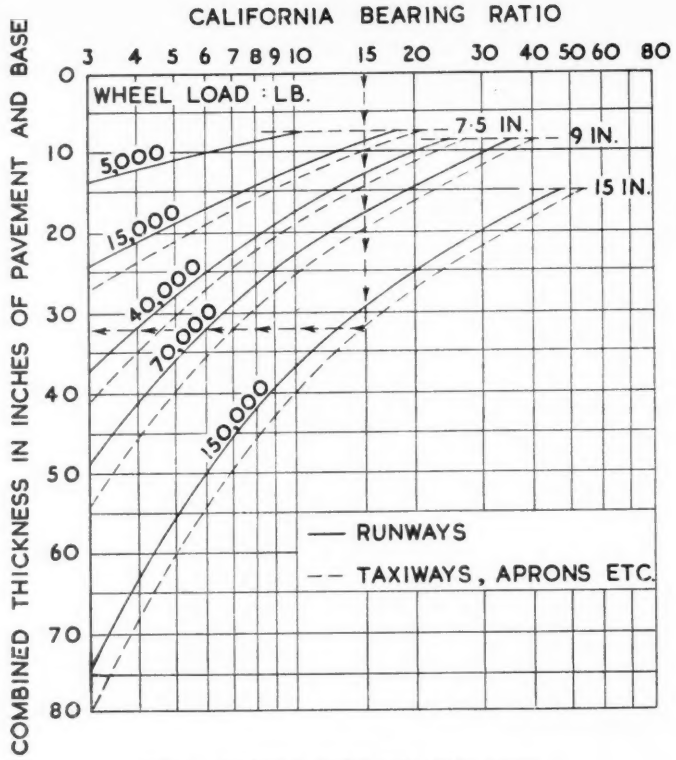


Fig. 3.—California bearing ratio design curves.

cracks in the surfacing down into the subgrade. These conditions may be severe in sub-tropical climates, such as the Middle East where runways 18 in. thick have destroyed themselves in this way.

Concrete pavements, unless they are properly designed, are liable to self-destruction. If the expansion joints are wrongly spaced or ineffective, severe cracking and disruptions can occur in hot weather, and poor quality concrete can disintegrate because of frost.

6.2. Design Methods

Available methods are

(*a*) Empirical—California Bearing Ratio (C.B.R.).
Group Index and other methods based on soil classification.

(*b*) Theoretical—Shear strength methods for flexible pavements, Equivalent Single Wheel Load method.
Westergaard's method for rigid pavements.

6.3. Empirical Methods

These are based on knowledge of the soil properties and practical experience, and take into account wheel loading and traffic intensity.

The California Bearing Ratio method is the most widely accepted empirical method for *flexible* pavements. The bearing ratio is derived from measurement of the load required to force a piston of 3 in.^{2} end area through prescribed distances into a sample of compacted soil or pavement material, or into an undisturbed sample of the subgrade soil. The result is expressed as a percentage of an ideal material such as crushed hard rock. For example, a well-graded sandy soil has a C.B.R. of about 25 per cent., but for a heavy clay soil it is only about 2 or 3 per cent.

The California Division of Highways drew up a series of curves, based on practical experience, relating wheel load, pavement, thickness, and C.B.R. These were extrapolated by the U.S. Army Engineers up to loads of 150,000 lb. on the results of large scale tests with heavy wheel loads, as shown in Fig. 3. Knowing the C.B.R. value of the soil and the maximum wheel loading the pavement thickness is read off directly.

An equivalent single wheel loading is assumed for multi-wheeled undercarriages, taking into consideration the spacing of the wheels. In recent years, modifications have been made to the design curves to account for variations in tyre pressure and wheel arrangements for multi-wheel undercarriages.

6.4. Theoretical Methods

Shear strength methods, such as that developed by Glossop and Golder, relate the shear stresses set up in the subgrade soil with the actual shear strength of the soil as determined by compression tests on soil samples. This method is restricted to flexible pavements on clay soils.

Burmister has attempted to compute the actual stress conditions set up in the pavement and subgrade, and has compared them with the actual strength characteristics of the materials.

The Equivalent Single Wheel Load method is used by the Air Ministry and is based on observations of plate bearing tests, using a plate diameter of the same order as heavy aircraft wheel loading. Computations are made to relate the deflections obtained by the tests to deflections of single- or multi-wheel aircraft undercarriages.

The Westergaard theory analyses the flexural stresses set up in rigid concrete pavements due to wheel loads. Allowances are made for the effect of slab-joints, stresses due to temperature effects and shrinkage of the concrete. To determine the flexural stresses, the wheel loads are related to the modulus of subgrade reaction, which is defined as the load in lb./in.^{2} on a loaded area of the subgrade divided by the deflection in inches of the subgrade under load. The modulus is determined from observations of the settlements of circular plates under different intensities of load.

Because of a number of uncertain factors, such as moisture movements in the concrete slab and friction between the slab and subgrade, the Westergaard theory cannot be regarded as an accurate method of design. It is the usual practice to design rigid pavements on the basis of past experience and large scale loading tests on experimental slabs, with the Westergaard theory used to give a rough idea of the paving thicknesses required.

The Westergaard method does enable the engineer to appreciate the stress conditions set up in the pavement by the wheel loading and it fully emphasises the value of high-quality concrete in giving economies in pavement thickness. An inch thickness of concrete costs, at present, about half-a-crown per square yard. Thus, by careful design methods a saving of one inch in thickness would give a saving of at least £150,000 on a standard heavy-bomber airfield which has something like 1,000,000 yd.^{2} of concrete paving.

7. Pavement Construction

Having decided the overall thicknesses required for the pavement, the engineer must consider next the nature of the constructional materials. For flexible pavements, the design methods give a minimum overall thickness of sub-base, base and surfacing. He can vary the thickness of each of these components in accordance with their quality. If the sub-base is a low-grade material, such as poorly graded quarry waste, he will need a fairly thick base and surfacing. On the other hand, a well-graded sand-gravel-clay sub-base will only require a thin base and surfacing, and it may be possible to omit the base altogether. Soil stabilised with cement is suitable for sub-base or base material if it is a granular material with a reasonably good grading. Stabilisation of clay soils is an uneconomical procedure in view of the high percentage of cement required (about 15 per cent.), and the lack of any efficient process for large-scale mixing. In tropical countries, local materials such as laterite or kankar are suitable for base construction.

The thickness of the surfacing again depends on the quality of the base material; a high quality base such as lean-mix concrete or well packed hard rock would require an asphalt or tarmacadam surface of only nominal thickness. The problems of weathering, petrol spillage, and jet engine blast, on bituminous surfaces have already been mentioned.

For rigid pavements the required thickness depends on the quality of the concrete, so the engineer must consider the availability of

concrete aggregates, the plant used for mixing and spreading, and the degree of control which he can impose on the contractor. He then fixes a minimum crushing strength, which for high quality work is about 4,000 lb./in.^{2} at an age of 28 days, and he proportions the pavement thickness accordingly. On a sandy or gravelly subsoil, the concrete pavement is laid directly on the subgrade, but on clay soils it is usual to provide a sub-base of gravel or lean-mix concrete to prevent softening of the soil by surface water, and to give a clean working area for the operations of fixing formwork and jointing strips.

Reinforcement is not normal practice in concrete runways, but load-transfer devices such as dowel bars between adjoining slabs are helpful in distributing wheel loads, and produce economies in thickness.

A smooth finish is desirable so as to shed water quickly and to save wear on aircraft tyres. The rough tamped finish sometimes seen on concrete roads is undesirable, since only a flat fall is given to the runway surface with the result that water would lie in the hollows caused by tamping, and in frosty weather the conditions would be dangerous.

The standard spacing for expansion joints is 120 ft., with contraction joints, to allow for shrinkage of the concrete, at 15 to 20 ft. centres.

8. OTHER PROBLEMS

The problems of drainage are beyond the scope of this paper, since they have no particular bearing on aeronautical engineering. Airfield lighting is more in the province of the electrical engineer. The civil engineer merely has to provide ducts and inspection pits for the vast network of cables which complicate his drainage layout, and interrupt the smooth working of the contractor laying the airfield paving.

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Oscillatory Occurrences in Ball Bearings

Premature Fatigue and its Elimination

by

Dr. M. S. FRENKEL

1. INTRODUCTION

In this paper it is shown how, in an angular contact ball bearing, the motion of a ball depends on the dimensions, loading and speed of the bearing. In general, ball motion in an angular contact bearing differs from the simple motion usually visualised by including oscillatory occurrences, shown here analytically, graphically and visually. These oscillatory occurrences are shown to lead to premature fatigue of the bearing metal, as a function of the speed of rotation, thereby imposing the present limitations on maximum speed and "life."

It is further shown that only when the dimensions of an angular contact ball bearing are related in a certain way, a motion is produced in which the oscillatory phenomena are eliminated. These relations are given as functions of loading and speed in a system of equations and limiting conditions (hereafter referred to as "Relations of the Dimensions").

Some fundamental considerations, and some of the equations, are contained in Ref. 1. The expression "true rolling" used in the earlier paper to denote the motion of a ball in a bearing constructed in accordance with the Relations of the Dimensions does not mean "rolling" as opposed to sliding in the contact areas, but applies to the absence in the ball's motion of the phenomena producing premature fatigue.

The paper gives first a new derivation of gyroscopic inertia couples, from which the couple can be visualised as a "couple of centrifugal forces." The resulting oscillations of angular velocities of a ball about different axes through its centre are shown.

The more important effects of couples on the balls formed by forces from the tracks are considered; these lead, in bearings not constructed in accordance with the Relations of the Dimensions, to a different kind of oscillation, hitherto unrecognised and denoted "pseudo-gyroscopic effect." It is shown how the resultant oscillations cause premature fatigue, as a function of speed, and lead to the present limitations of maximum speed and life.

In connection with the life of bearings, whereas in an ordinary machine-element subject to repetitive loading fatigue will cause failure after limited numbers of repetitions for loadings above a certain limit called the "fatigue limit" while below that limit any number of repetitions will not produce failure, existing ball bearings have no lower limit of loading below which fatigue will not occur, due to the phenomena already mentioned.

After formulation of conditions relating to "conformity" necessary to ensure that the ball motion is free from harmful oscillatory effects, the full system of equations for the Relations of the Dimensions is given, and it is shown that bearings using them are applicable for ranges of speeds and of loading conditions.

NOTATION

x, y, z = rectangular co-ordinates defined in the text
r = ball radius
R = radius of the path of the ball centre (pitch-circle radius)

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M = ball mass

I = polar moment of inertia of ball

$k = \dfrac{I}{Mr^2} = 0.4$ for a solid, homogeneous ball

α_2 = angle between the axis of symmetry A_2CF_2 of the groove profile in the inner bearing ring and the normal to the bearing axis OO (*see* Fig. 5)
(With the inner ring stationary, α_2 is also the angle of contact of the bearing, *i.e.* the angle between the rolling axis (x) of the ball normal to A_2CF_2, and bearing axis OO)

α_1 = angle corresponding to α_2 for the outer track, between A_1CF_1 and the normal to OO

$\vartheta = \alpha_2 - \alpha_1$

$N_1\ N_2$ = resultants of the pressure forces in the contact areas between the outer and inner tracks and the ball, respectively

α_0, α_x = angles at O shown in Fig. 5

θ_1, θ_2 = half the angle subtended at C by the widths B_1E_1 and B_2E_2 of the contact areas between the ball and the outer and inner rings respectively

r_{F1}, r_{F2} = radii of curvature of the groove profiles ($= F_1B_1$ and F_2B_2 respectively)

P_t = external axial load on the bearing

t = axial pressure force component on a ball (*see* Fig. 5)

n = number of balls in the race

μ = a coefficient of friction

μ_S = coefficient of sliding friction between ball and track

δ_1, δ_2 = coefficients (equivalent lever arm) of rolling resistance of the ball on the tracks

ω_S = speed of rotation of the driving bearing ring

ω_R = rolling angular velocity of the ball

ω_b = angular velocity of ball about z-axis

ω_c = angular velocity of the ball centre about OO

ω = resultant angular velocity of the ball

V_c = circumferential velocity of the ball centre

$T_R, T_x, T_y, T_{Rx}, T_{Ry}, T_{Fx}, T_{Fy}$ = friction couples defined in the text

S = contact area between the ball and track

J_1, J_2 = couples acting on the ball due to the friction forces (*see* Section 5)

ξ_R, ξ_y = defined by equations (42) and (43)

2. COUPLES OF CENTRIFUGAL FORCES

The gyroscopic effect will, for simplicity, first be considered for an axial ball bearing (as an extreme case of an angular contact bearing) (*see* Fig. 1) in which the motion of the ball is free from harmful phenomena. As shown in Section 4, Case III, this motion is such that the axis of the rolling angular velocity of the ball passes always through the same two points on the surface; this will occur only in a bearing observing the Relations of the Dimensions. In such a ball motion the effects of the gyroscopic couples and of opposing couples will be represented; in certain conditions these cancel out. Section 3 deals with the harmful phenomena which arise when the effects do not cancel out and, from this, one condition for the Relations of the Dimensions is derived.

In the motion (*see* Fig. 1) the ball rotates, together with the axis OCA_x (x-axis) of its rolling angular velocity ω_R, with the same angular velocity ω_c about the axis CC (z-axis) through its centre C and parallel to the bearing axis OO, as the ball centre C itself has in its circular motion about OO (*see* Section 4, Case III). Hence, in time dt the vector CA_x of the rolling angular velocity ω_R describes an angle $A_xCB_x=\omega_c dt$ bringing it into the position CB_x.

What does this mean with regard to the motion of a particle of mass of the ball in any position therein?

Consider a particle L_1, of mass dM, which at instant t has the co-ordinates $y_{(t)}$ and $z_{(t)}$ in an orthogonal plane system (y_1, z_1) (*see* Fig. 2). The plane of co-ordinates is normal to the rolling axis OCA_x of the ball, the z_1-axis is parallel to CC and hence also to OO, and the origin is at C_1, a distance $CC_1=-x$ from the ball centre C.

At time t the particle L_1 has the velocity

$$v_{\rho(t)}=\rho\omega_R \qquad . \quad . \quad . \quad . \quad . \quad (1)$$

in the y_1z_1-plane, where $\rho=C_1L_1$. The velocity vector v_ρ encloses an angle ϕ with the y_1-axis, so that its component in the y-direction is

$$v_{y(t)}=v_{\rho(t)}\cos\phi=\rho\omega_R\cos\phi=z_{(t)}\omega_R \qquad . \quad (2)$$

and its component in the z-direction is similarly

$$v_{z(t)}=y_{(t)}\omega_R \qquad . \quad . \quad . \quad . \quad . \quad (3)$$

Normal to the y_1z_1-plane, *i.e.* in the x-direction, the velocity of particle L_1 at time t is

$$v_{x(t)}=y_{(t)}\omega_c, \qquad . \quad . \quad . \quad . \quad . \quad (4)$$

because, since the bearing is constructed in accordance with the Relations of the Dimensions, the ball, with all planes intersecting it normally to rolling axis OCA_x (x-axis), rotates with the angular velocity $\omega_b=\omega_c$ about the polar axis CC, and since thus the plane y_1z_1 rotates as part of the ball with angular velocity ω_c about CC, it it also rotates with the same angular velocity about any axis parallel to it, *i.e.* axis z_1, as shown in Ref. 1, Appendix I. (In a bearing not observing the Relations of the Dimensions, the plane y_1z_1 normal to the axis OCA_x would continually coincide with different planes of the ball (*see* Section 4).)

To determine the acceleration dv_x/dt of L_1 in the x-direction due to the rotation of the y_1z_1-plane with angular velocity ω_c about the z_1-axis, it is necessary to consider first all the changes in the co-ordinates of L_1, as well as the changes in the velocities of L_1 which occur in the time element dt following the instant t already considered.

At $(t+dt)$ the co-ordinates of L_1 will have changed, bringing L_1 to position L_1'' in its plane y_1z_1, as follows:—

Because of the displacement of L_1' to L_1'' by distance $v_y dt$ in the direction of the y-co-ordinate, $y_{(t)}$ will have changed to

$$y_{(t+dt)}=y_{(t)}+v_y dt=y_{(t)}+z_{(t)}\omega_R dt \qquad . \quad . \quad . \quad . \quad (5)$$

and similarly, due to the displacement of L_1 to L_1', $z_{(t)}$ will have become

$$z_{(t+dt)}=z_{(t)}+v_z dt=z_{(t)}+y_{(t)}\omega_R dt. \qquad . \quad . \quad . \quad . \quad (6)$$

It will be shown that, due to the change in the y-co-ordinate of L_1 by $v_y dt$, and due to the change of direction of the velocity vector v_y by angle $\omega_c dt$ (because of the

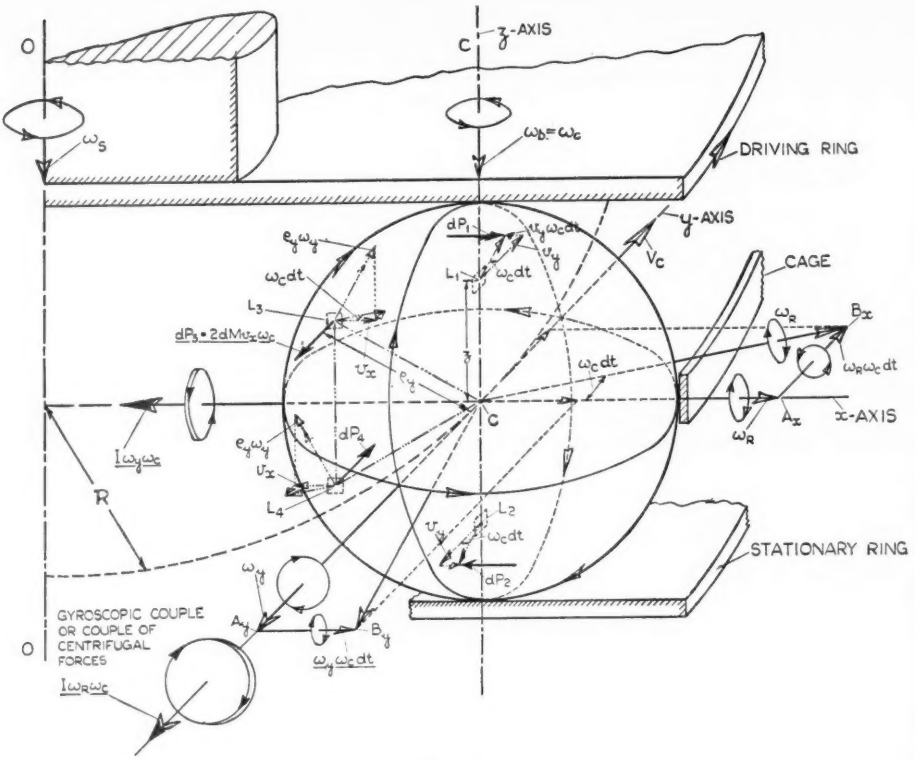

Fig. 1.

rotation of the y_1z_1-plane with angular velocity ω_c about the z_1-axis), the change of velocity of L_1 in the x-direction in time dt will consist of two parts,

$$v_{x(t+dt)} - v_{x(t)} = d_1v_x + d_2v_x, \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Hence the acceleration of L_1 in the x-direction is

$$\frac{dv_x}{dt} = \frac{d_1v_x}{dt} + \frac{d_2v_x}{dt}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

The part d_1v_x arises because the velocity normal to the y_1z_1-plane, which at t was $v_{x(t)} = y_{(t)}\omega_c$, has become, substituting from (5),

$$v_{x(t+dt)_1} = y_{(t+dt)}\omega_c = (y_{(t)} + v_y dt)\omega_c = (y_{(t)} + z_{(t)}\omega_R dt)\omega_c. \quad . \quad . \quad (9)$$

Hence

$$d_1v_x = v_{x(t+dt)_1} - v_{x(t)} = v_y\, dt\, \omega_c = z_{(t)}\omega_R\, dt\, \omega_c \quad . \quad . \quad (10)$$

and the first part of the acceleration is

$$\frac{d_1v_x}{dt} = v_{y(t)}\omega_c = z_{(t)}\omega_R\omega_c. \quad . \quad . \quad . \quad . \quad . \quad (11)$$

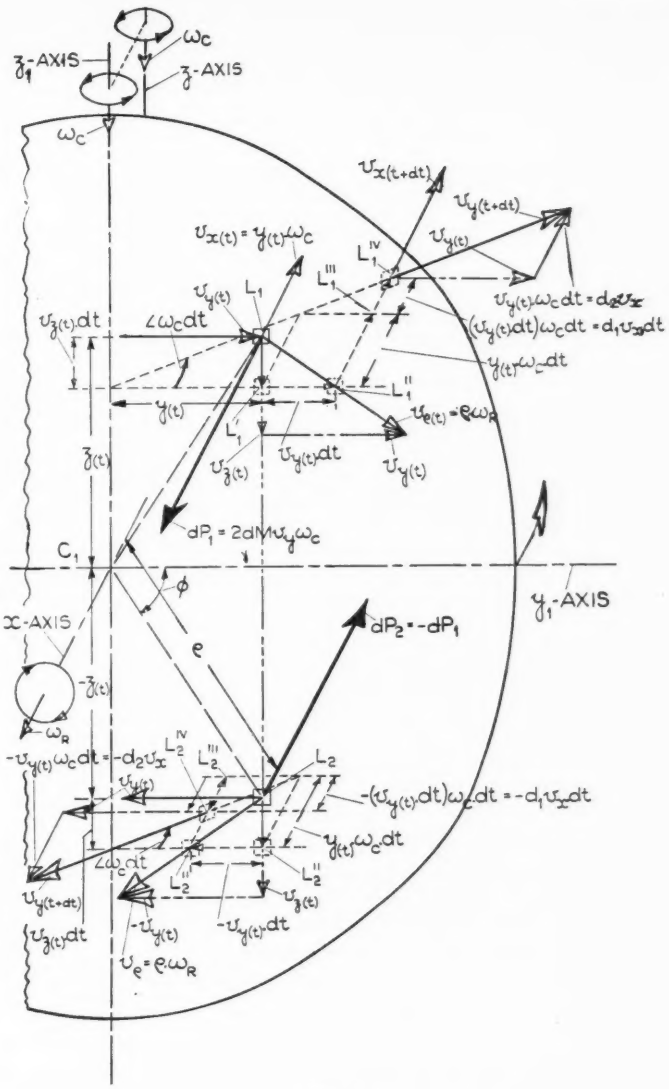

Fig. 2.

The second part, d_2v_x, arises as follows. While the velocity vector $v_{y(t)}$ of L_1 lies in the y_1z_1-plane and thus has, in the x-direction, the component

$$v_{yn(t)}=0, \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

the velocity vector $v_{y(t+dt)}$ makes, due to the rotation of its plane, the angle $\omega_c dt$ with the y_1z_1-plane and hence with $v_{y(t)}$, and hence it makes the angle $(\pi/2-\omega_c dt)$ with the x-direction, so that the component of velocity vector $v_{y(t+dt)}$ in the x-direction is

$$v_{yn(t+dt)}=v_{y(t)}\sin(\omega_c dt)=v_{y(t)}\omega_c dt=z_{(t)}\omega_R\omega_c dt. \quad . \quad . \quad (13)$$

Hence, using equations (13), (12) and (3),

$$d_2v_x = v_{yn\,(t+dt)} - v_{yn\,(t)} = v_{y\,(t)}\omega_c\,dt - 0 = z_{(t)}\omega_R\omega_c\,dt \quad . \quad . \quad (14)$$

and the second part of the acceleration is

$$\frac{d_2v_x}{dt} = v_{y\,(t)}\omega_c = z_{(t)}\omega_R\omega_c. \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

The total acceleration of L_1 in the x-direction, in the motion described (*see* Fig. 2) is thus, from (11) and (15),

$$\frac{dv_x}{dt} = \frac{d_1v_x}{dt} + \frac{d_2v_x}{dt} = 2z\omega_R\omega_c \quad . \quad . \quad . \quad . \quad . \quad (16)$$

which produces an inertia-force dP_1, acting in the opposite direction, equal to

$$dM\,\frac{dv_x}{dt} = dP_1 = dM\,2z\omega_R\omega_c. \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

From equations (10) and (14) for d_1v_x and d_2v_x, it follows that dP_1 equals double the centrifugal force due to a change of direction of velocity vector v_y by the angle $\omega_c dt$; this enables the direction of action of dP_1 to be visualised immediately.

Similarly, for the particle L_2 of mass dM, which at instant t has co-ordinates $-z_{(t)}$, $y_{(t)}$, as shown in Fig. 2, the inertia force due to the corresponding motion is

$$dP_2 = -2dMz\omega_R\omega_c = -dP_1. \quad . \quad . \quad . \quad . \quad . \quad (18)$$

This may again be considered as double the centrifugal force, but acting in the opposite direction to dP_1, since the velocity vector $v_{y\,(t)}$ is in the opposite direction to $v_{y\,(t)}$ of L_1, as shown in Fig. 2.

Because of the rotation of each plane of the ball, normal to OCA_x, with angular velocity ω_c about the z-axis, each particle in such a plane will generally act normally to its plane with an inertia force which represents a double centrifugal force, because of the tendency of maintaining the direction of v_y constant. Further, each of two particles of mass dM which are in the same plane normal to OCA_x and situated symmetrically about the y-axis, will act with oppositely directed inertia forces normal to their plane, their velocities v_y being in opposite directions; these forces together form a couple with arm $2z$ tending to rotate their zy-plane about the y-axis. The magnitude of each such couple is

$$2z\,2dM\,z\omega_R\omega_c = 4z^2dM\omega_R\omega_c \quad . \quad . \quad . \quad . \quad . \quad (19)$$

Since each such couple concerns two particles of mass dM each, the total number of couples for the whole ball of mass M is $M/(2dm)$, so that taking the sum of the couples between the limits 0 and $M/2$ will take in the whole ball. Hence the total couple of centrifugal forces, acting about the y-axis, is

$$\int_0^{M/2} 4z^2dM\omega_R\omega_c = \int_0^{M} 2z^2dM\omega_R\omega_c. \quad . \quad . \quad . \quad . \quad . \quad (20)$$

Further, since the ball is symmetrical about all axes through its centre of gravity,

$$\int_0^{M} z^2dM = \int_0^{M} y^2dM = \int_0^{M} x^2dM \quad . \quad . \quad . \quad . \quad . \quad (21)$$

so that

$$\int_0^{M} 2z^2dM\omega_R\omega_c = \int_0^{M} (z^2+x^2)dM\omega_R\omega_c = I\omega_R\omega_c, \quad . \quad . \quad . \quad . \quad (22)$$

where I is the polar moment of inertia of the ball.

$I\omega_R\omega_c$ is thus the magnitude of the total couple of centrifugal forces, or gyroscopic inertia couple, which tends to rotate the ball in the plane containing the x- and z-axes of its angular velocities ω_R and ω_c respectively, *i.e.* about the y-axis, in the sense of rotation indicated in Fig. 1.

In order to prevent a rotation about the y-axis arising due to $I\omega_R\omega_c$, there must be an external "couple of centripetal forces" T_y such that

$$T_y - I\omega_R\omega_c = 0. \quad . \quad . \quad . \quad . \quad . \quad (23)$$

3. OSCILLATIONS OF ANGULAR VELOCITIES DUE TO GYROSCOPIC EFFECTS

The only external couple acting on the ball in the plane through C and normal to the y-axis, as a couple of centripetal forces, is the couple of the friction forces from the tracks. For large angular velocities of the rotating bearing ring, giving rise to large values of ω_c and ω_R, the friction couple attains a limiting value $T_y < I\omega_R\omega_c$, so that then

$$I\omega_R\omega_c - T_y = I\frac{d\omega_y}{dt} \quad . \quad . \quad . \quad . \quad . \quad (24)$$

Hence a new angular velocity of the ball, ω_y, about the y-axis, arises from the couple $I\omega_R\omega_c$. In time t this new angular velocity will have attained a magnitude ω_y given by

$$\int_0^t I\omega_R\omega_c\,dt - \int_0^t T_y\,dt = I\omega_y \quad . \quad . \quad . \quad . \quad (25)$$

as indicated by the vector CA_y on Fig. 1.

Accordingly, there are at time t two angular velocities whose vectors $\omega_R = CA_x$ in the x-axis and $\omega_y = CA_y$ in the y-axis both rotate with angular velocity ω_c about the z-axis (*see* Fig. 1).

Hence a particle such as L_1 (*see* Fig. 2), with co-ordinates $y_{(t)}, z_{(t)}$ and velocity $\rho\omega_R$, due to the rotation ω_R about the x-axis, will have additionally the velocity $\rho_y\omega_y$ in the xz-plane normal to the y-axis, due to the angular velocity ω_y about the y-axis. This will hold for all particles of mass dM, such as L_3 (x_3, z_3), and L_4 $(x_3, -z_3)$, in the xz-plane shown in Fig. 1. This plane rotates with angular velocity ω_c about the z-axis (CC), and applying to the velocity vectors $\rho_y\omega_y$ of L_3 and L_4 the same considerations as were applied to the velocity vectors $\rho\omega_R$ of L_1 and L_2, gives the sum of the couples of centrifugal forces for the whole ball as $I\omega_y\omega_c$, tending to rotation about the x-axis.

In order that no such rotation should arise, there must be an external couple of centripetal forces given by

$$T_x - I\omega_y\omega_c = 0. \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

(This is represented vectorially on Fig. 1, as follows:—In time dt the vectors $\omega_R = CA_x$ and $\omega_y = CA_y$ rotate through an angle $\omega_c dt$, coming into positions CB_x and CB_y respectively, where $A_xB_x = \omega_R\omega_c dt$ and $A_yB_y = \omega_y\omega_c dt$ represent their changes. To a scale $1/dt$, A_xB_x and A_yB_y represent, in magnitude and direction, the required couples of centripetal forces.)

The only external couple on the ball in the plane normal to the x-axis is the couple of the friction forces from the track T_x which, while $I\omega_y\omega_c$ increases continuously with ω_y, from (25), can only increase to its limiting value T_R, so that finally $T_R < I\omega_y\omega_c$ and

$$I\omega_y\omega_c - T_R = I\frac{d\omega_x}{dt}. \quad . \quad . \quad . \quad . \quad . \quad (27)$$

To determine the direction of rotation about the x-axis due to $I\omega_y\omega_c$, consider L_3 and L_4, which have velocities $\rho_y\omega_y$ in their xz-planes, with x-components equal to $v_x = z\omega_y$ (*see* Fig. 1).

From the same considerations as for L_1 the particle L_3 will be seen to exert an inertia force $dP_3 = 2dMz\omega_y\omega_c$, equal to double the centrifugal force, normal to the xz-plane, against the rotation of the velocity component v_x with angular velocity ω_c about the z-axis. Similarly L_4, situated in the same xz-plane symmetrically about the x-axis, will exert an inertia force dP_4, equal to double the centrifugal force but in the opposite direction to dP_3, because the velocity component v_x of L_4 is in the opposite direction. Forces dP_3 and dP_4 form a couple which tends to rotate the ball about the x-axis in a direction opposite to the angular velocity ω_R.

Hence

$$d\omega_x = -d\omega_R \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

so that equation (27) becomes

$$I\omega_y\omega_c - T_R = -I\frac{d\omega_R}{dt} \quad . \quad . \quad . \quad . \quad . \quad . \quad (29)$$

Equations (24) and (29) relate the angular velocities ω_y and ω_R of the ball.

Since the characteristics of the oscillations of ω_y and ω_R can be obtained only from their second order differential equations, equations (24) and (29) are differentiated with respect to t, giving

$$\frac{d^2\omega_y}{dt^2} = \omega_c\frac{d\omega_R}{dt} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

$$\frac{d^2\omega_R}{dt^2} = -\omega_c\frac{d\omega_y}{dt} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

From equations (24) and (31),

$$\frac{d^2\omega_R}{dt^2} = -\omega_c^2\left(\omega_R - \frac{T_y}{I\omega_c}\right) \quad . \quad . \quad . \quad . \quad . \quad (32)$$

and from equations (30) and (29),

$$\frac{d^2\omega_y}{dt^2} = -\omega_c^2\left(\omega_y - \frac{T_R}{I\omega_c}\right). \quad . \quad . \quad . \quad . \quad . \quad (33)$$

Since $T_y/(I\omega_c)$ and $T_R/(I\omega_c)$ are constants, equations (32) and (33) can be written

$$\frac{d^2}{dt^2}\left(\omega_R - \frac{T_y}{I\omega_c}\right) = -\omega_c^2\left(\omega_R - \frac{T_y}{I\omega_c}\right) \quad . \quad . \quad . \quad . \quad (34)$$

$$\frac{d^2}{dt^2}\left(\omega_y - \frac{T_R}{I\omega_c}\right) = -\omega_c^2\left(\omega_y - \frac{T_R}{I\omega_c}\right). \quad . \quad . \quad . \quad (35)$$

If

$$\left(\omega_R - \frac{T_y}{I\omega_c}\right) = \xi_R \quad . \quad . \quad . \quad . \quad . \quad . \quad (36)$$

$$\left(\omega_y - \frac{T_R}{I\omega_c}\right) = \xi_y \quad . \quad . \quad . \quad . \quad . \quad . \quad (37)$$

it is seen that equations (34) and (35) are of the general form

$$\frac{d^2}{dt^2}(\xi) = -\omega_c^2(\xi) \quad . \quad . \quad . \quad . \quad . \quad . \quad (38)$$

i.e. a simple harmonic oscillation of period $2\pi/\omega_c$.

The general solution of (38) is

$$\xi = A\cos(\omega_c t) + B\sin(\omega_c t). \quad . \quad . \quad . \quad . \quad (39)$$

The relation between ξ_R and ξ_y is determined as follows:—

Since ω_y is caused by the gyroscopic couple $I\omega_R\omega_c$, it will reach a maximum, and hence also ξ_y (from (37)) will reach a maximum, when

$$I\omega_R\omega_c - T_y = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (40)$$

i.e. when

$$\omega_R - \frac{T_y}{I\omega_c} = \dot{\xi}_R = 0. \quad . \quad . \quad . \quad . \quad . \quad (41)$$

Hence $\xi_y = \xi_{y\max}$ when $\dot{\xi}_R = 0$, and similarly from (29), $\xi_R = \xi_{R\max}$ when $\dot{\xi}_y = 0$, which means that $\dot{\xi}_y$ and $\dot{\xi}_R$ have a phase displacement of $\pi/2$, so that

$$\xi_R = A\cos(\omega_c t) = \left(\omega_{R\max} - \frac{T_y}{I\omega_c}\right)\cos(\omega_c t) \quad . \quad . \quad . \quad (42)$$

$$\xi_y = B\sin(\omega_c t) = \left(\omega_{y\max} - \frac{T_R}{I\omega_c}\right)\sin(\omega_c t). \quad . \quad . \quad . \quad (43)$$

$\omega_{R\max}$ is the angular velocity of true rolling, given by

$$\omega_{R\max} = \frac{R\omega_c}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

since $I\omega_y\omega_c$, when it begins to produce a rotation, reduces ω_R from its value for true rolling, which is therefore its maximum value.

This gives the solutions

$$\omega_y = \left(\omega_{R\max} - \frac{T_y}{I\omega_c}\right)\cos(\omega_c t) + \frac{T_y}{I\omega_c} \quad . \quad . \quad . \quad . \quad (45)$$

$$\omega_R = \left(\omega_{y\max} - \frac{T_R}{I\omega_c}\right)\sin(\omega_c t) + \frac{T_R}{I\omega_c} \quad . \quad . \quad . \quad . \quad (46)$$

i.e. both angular velocities ω_R and ω_y oscillate about respective mean values

$$\omega_{R\,\mathrm{mean}} = \frac{T_y}{I\omega_c} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

$$\omega_{y\,\mathrm{mean}} = \frac{T_R}{I\omega_c}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (48)$$

having a phase difference of $\pi/2$, as shown in Fig. 3.

It is shown in Section 4, Case II how such oscillations, in combination with others described in Section 4, lead to periodic impulses of high frequency of the ball against the track and produce premature fatigue.

The conditions that the gyroscopic couple acting on a ball should not produce such oscillations are now determined for the general case of an angular contact ball bearing in which the rolling axis of the ball encloses an angle of contact $\alpha_2 < 90°$ with the bearing axis (*see* Fig. 5).

The gyroscopic inertia couple in the xz-plane (the plane of the drawing) is $I\omega\sin(\alpha_2 - \alpha_0)\omega_c$, where ω is the vector of the resultant angular velocity, which encloses the angle $(\alpha_2 - \alpha_0)$ with the bearing axis OO, α_2 is the angle of contact of the bearing between the rolling axis x and OO, and α_0 is the angle between ω and x (*see* Ref. 1 p. 222).

ω has a component vector $\omega\cos(\alpha_2 - \alpha_0)$ parallel to OO, which does not change direction while the ball moves in its circular path and thus has no gyroscopic effect,

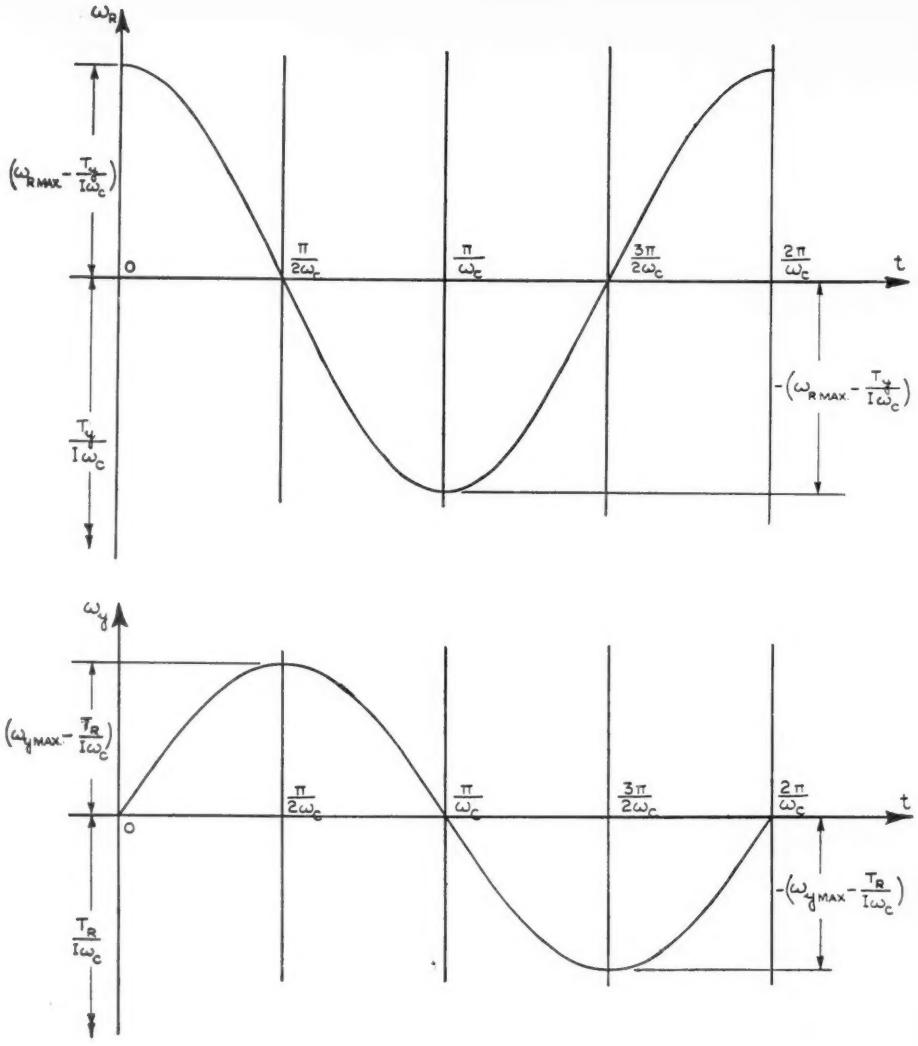

Fig. 3.

while the component vector $\omega \sin(\alpha_2 - \alpha_0)$ normal to OO changes its direction with angular velocity ω_c; this gives rise to the gyroscopic inertia couple $I\omega \sin(\alpha_2 - \alpha_0)\omega_c$.

If this gyroscopic couple causes no rotation of the ball in the xz-plane, from equation (24)

$$I\omega \sin(\alpha_2 - \alpha_0)\omega_c - T_y = 0. \quad . \quad . \quad . \quad . \quad (49)$$

Now

$$T_y = T_y' + T_y'', \quad . \quad . \quad . \quad . \quad . \quad (50)$$

where T_y' is the couple of the friction forces from the track in the xz-plane and T_y'' is the friction couple from the cage (not shown).

$$T_y' = N_1 \mu (2r) \quad . \quad . \quad . \quad . \quad . \quad . \quad (51)$$

where N_1 is the resultant pressure force between ball and driving track (*see* Fig. 5). From the triangle of forces $A_1A_3A_4$,

$$N_1 = \frac{t}{\sin \alpha_1} = \frac{P_t}{n \sin (\alpha_2 - \vartheta)} \quad . \quad . \quad . \quad . \quad (52)$$

where $t\,(=P_t/n)$ is the axial pressure force on one ball, P_t the external axial load on the bearing, n the number of balls in the race and $\vartheta = \alpha_2 - \alpha_1$ is the angle between the constructed axes of symmetry of the groove profiles A_1CF_1 and A_2CF_2.

Further, from the angular velocity vectors of the ball, as shown on Fig. 5,

$$\omega = \frac{\omega_c \sin \alpha_2}{\sin \alpha_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad (53)$$

and the polar moment of inertia of the ball is $I = 0.4Mr^2$.

Substituting from (50), (51), (52) and (53) into (49) gives

$$Mrn\left(\frac{R}{r} - \cos \alpha_2 \sin \alpha_2\right) \sin (\alpha_2 - \vartheta) = \frac{P_t}{\omega_c^2} \frac{2\mu}{0.4} + T_y'' \quad . \quad . \quad (54)$$

as condition for no gyroscopic rotation of the ball to arise.

Taking μ as $\frac{1}{2}\mu_S$, because of the relative angular velocities between the ball and its tracks in their respective contact areas and the friction considerations in the note on p. 219 of Ref. 1, the limiting condition is obtained as

$$Mrn\left(\frac{R}{r} - \cos \alpha_2 \sin \alpha_2\right) \sin (\alpha_2 - \vartheta) \leqslant \frac{P_t}{\omega_c^2} \frac{\mu_S}{0.4} . \quad . \quad . \quad (55)$$

ω_c is expressed in terms of the velocity of the driving bearing ring, ω_S, as

$$\omega_c = \omega_S \frac{R + \cos (\alpha_2 - \vartheta)}{[R (\cos \vartheta + 1) + r \sin \alpha_2 \sin \vartheta]} \quad . \quad . \quad . \quad (56)$$

from considerations of the angular velocity vectors in Fig. 5.

4. PSEUDO-GYROSCOPIC EFFECTS

The main phenomena leading to premature fatigue in bearings not observing the Relations of the Dimensions are now represented, and also the ball motion free from such phenomena. For simplicity an axial ball bearing is considered first (*e.g.* Fig. 1).

In an axial bearing not constructed in accordance with the Relations of the Dimensions, in which the ball centres rotate with an angular velocity ω_c about the bearing axis, a ball will not attain the same angular velocity about the axis CC through its centre and parallel to the bearing axis OO, but an angular velocity $\omega_b < \omega_c$. In a bearing observing the Relations of the Dimensions each ball will attain the angular velocity $\omega_b = \omega_c$ about CC.

To show what this means, three kinds of motion are described (*see* Fig. 4):—

(I) $\omega_b = 0$; (II) $\omega_b < \omega_c$; (III) $\omega_b = \omega_c$.

All three cases are represented through the motion of a system of co-ordinates xyz, whose z-axis is the line CC through the ball centre C and parallel to the bearing axis

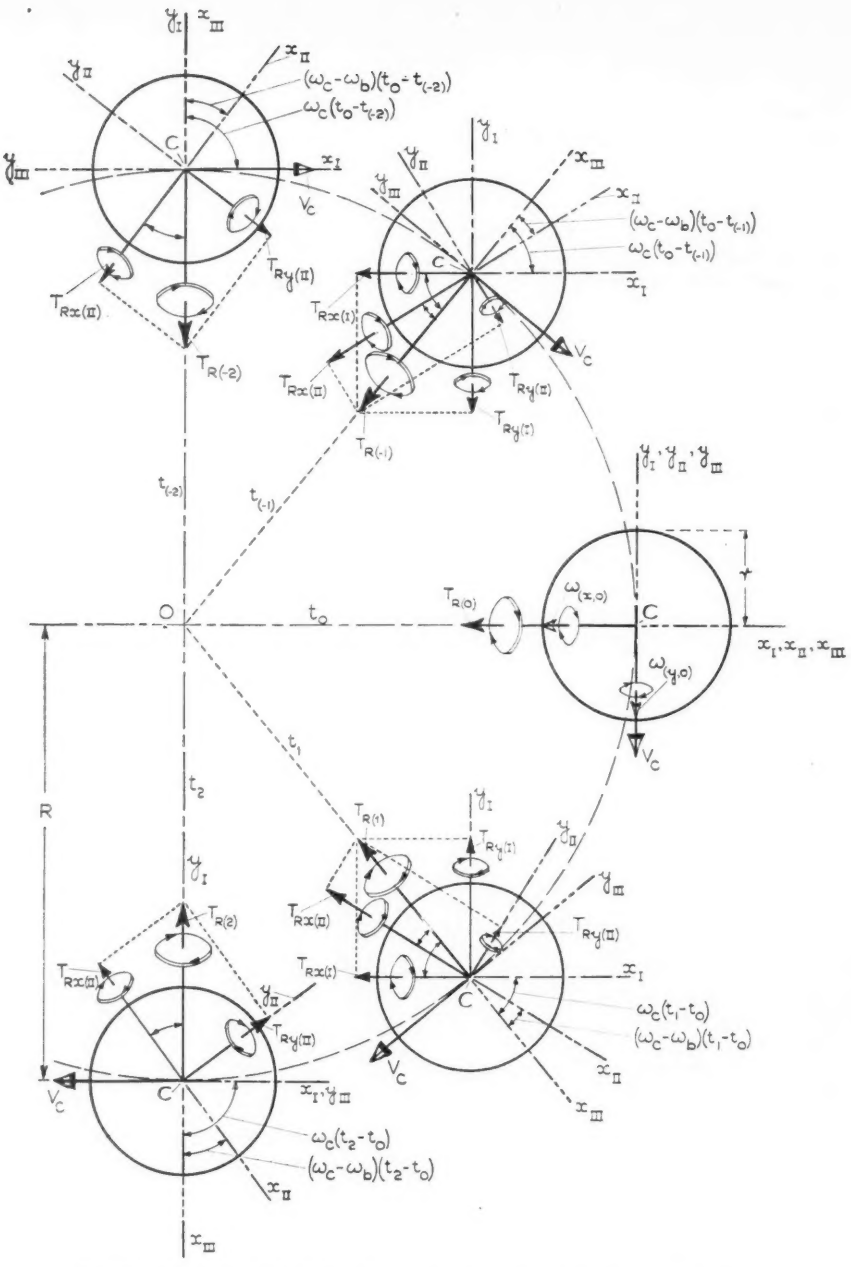

Fig. 4.—Plan view of a ball describing a circular path on a flat horizontal plane.

OO, whose origin is the ball centre C moving with angular velocity ω_c about OO, and whose xy-plane rotates about the z-axis with the same angular velocity ω_b as the ball.

CASE I: With $\omega_b=0$, the xy-plane does not rotate about the z-axis. If the axes x and y are denoted x_I and y_I, and if, for the zero position of the ball at time t_0, the x-axis coincides with the rolling axis OC of the ball and the y-axis with the velocity vector V_c of the ball centre C, then x_I and y_I remain parallel to themselves for all positions of C, as shown. Therefore at time t_1, the rolling axis OC, which then encloses the angle $\omega_c(t_1-t_0)$ with its position at instant t_0, will enclose the same angle with the axis x_1 at instant t_1, *i.e.* OC rotates with angular velocity ω_c about the z-axis with reference to the x_Iy_I-plane, and hence also with reference to the ball.

Friction forces from the tracks, arising from the circumferential velocity V_c of C (*see* Fig. 4) and acting in the plane containing the vector V_c and CC, form a couple T_R in that plane. T_R tends to produce a "rolling" motion, *i.e.* it makes the ball rotate about a rolling axis OC (the axis through C and normal to V_c) normal to its plane. Since OC rotates with angular velocity ω_c about CC (z-axis), the plane of T_R and hence also its vector (coincident with CO) rotate with angular velocity ω_c about the z-axis relative to the x_Iy_I-plane.

It follows that in a time interval $\tau_I=2\pi/\omega_c$ the vector T_R will describe a complete circle in the x_Iy_I-plane (having in this case no rotation about the z-axis), *i.e.* each radius vector of this circle, at some instant during this time interval, will coincide with the vector of T_R, when the radius vector will be referred to as the "instantaneous axis of rolling" of the ball. T_R acts at every instant in a different diametral plane of the ball, continually producing angular accelerations in these planes, *i.e.* the line of intersection of the plane of T_R with the x_Iy_I-plane also describes an angle 2π in the interval $\tau_I=2\pi/\omega_c$.

From Fig. 4 it will be seen that at time t_1 the vector of T_R has components in the x_I and y_I axes given by

$$T_{Rx1}=T_R\cos[\omega_c(t_1-t_0)] \quad . \quad . \quad . \quad . \quad (57)$$

and

$$T_{Ry1}=T_R\sin[\omega_c(t_1-t_0)] \quad . \quad . \quad . \quad . \quad (58)$$

so that the couples acting normally to the x_I- and y_I-axis vary in magnitude with a sinusoidal oscillation.

Thus, the angular velocity $\omega_{(x,0)}$ of the ball at instant t_0 about the x_I-axis, which is at that instant its instantaneous axis of rolling, will not suddenly have arisen due to the vector of couple T_R coinciding with axis x_1, but will have started before t_0 because T_R already had a component in the x_I-axis, which produced an angular acceleration of the ball about the x_I-axis in the same sense of rotation from the instant when the angle between x_I and T_R became less than $\pi/2$. In fact, a component of T_R acts in a plane normal to the x_I-axis and tends to rotate the ball about this axis in one sense of rotation while the angle between x_I and T_R is between $-\pi/2$ and $+\pi/2$, *i.e.* during the time interval $\frac{1}{2}\pi/\omega_c$ before and after t_0. Before and after this time interval, T_R also has components in the x_I-axis, but these will act in the opposite direction.

The angular velocities $\omega_{(x,0)}$ and $\omega_{(y,0)}$, which T_R will have produced at instant t_0, are given by

$$\int_{t_{(-2)}}^{t_0} T_R\cos(\omega_c t)\,dt-\int_{t_{(-2)}}^{t_0} T_{Fx}\,dt=I(\omega_{(x,0)}-\omega_{(x,-2)}) \quad . \quad . \quad . \quad (59)$$

and

$$\int_{t_{(-2)}}^{t_0} T_R\sin(\omega_c t)\,dt-\int_{t_{(-2)}}^{t_0} T_{Fy}\,dt=I(\omega_{(y,0)}-\omega_{(y,-2)}) \quad . \quad . \quad (60)$$

where $\omega_{(x,-2)}$ and $\omega_{(y,-2)}$ are the angular velocities of the ball about the x_I- and y_I-axes respectively at time $t_{(-2)}=t_0-\frac{1}{2}\pi/\omega_c$. T_{Fx} and T_{Fy} are the couples of the friction forces in the planes normal to the axes x_I and y_I respectively. They arise from the angular velocities of the ball about these axes and oppose these rotations, which are caused by the couple T_R.

From this consideration, and with reference to the footnote on p. 219 of Ref. 1 it can be seen that the left hand sides of (59) and (60) must be positive.

Summarising, at t_0 the ball has an angular velocity $\omega_{(x,0)}$ about the x_I-axis (the instantaneous axis of rolling), and an angular velocity $\omega_{(y,0)}$ about the y_I-axis, each of which reach maximum values at positions at which the respective components of couple T_R producing them are zero. After this, the angular velocities will be reduced by components of T_R, acting in the opposite directions about the same axes, until minimum values are reached, and so on; *i.e.* the angular velocities about the x_I- and y_I-axes oscillate.

More particularly, it will be seen that, for example, at instant $t_{(-2)}$ the axis y_I represents the instantaneous axis of rolling, while in the diametrically opposite position at instant $t_{(+2)}$ the same axis y_I represents the instantaneous axis of rolling again, but with the rolling angular velocity in the opposite direction. This shows that for some kind of rolling motion to be taking place the ball must have passed through a position in between at which the angular velocity about the y_I-axis was instantaneously zero, and that, for the whole circuit of the ball, there must be a position of maximum angular velocity about y_I in one direction, and another position for a minimum, *i.e.* for a maximum in the opposite direction.

The foregoing considerations, arrived at by following the axes x_I and y_I, apply similarly to each set of orthogonal axes in the x_Iy_I-plane (in which the vector of couple T_R rotates), the angular velocities about such axes oscillating between maximum and minimum values and passing through zero in the process. Conversely, at each circumferential position in the race, a ball will have an angular velocity about its instantaneous axis of rolling and about the axis normal to it in the xy-plane, the angular velocities oscillating between maximum and minimum values.

CASE II: This case, $0<\omega_b<\omega_c$, generally occurs in ball bearings not constructed in accordance with the Relations of the Dimensions. Consider (*see* Fig. 4) a second system of co-ordinates $x_{II}y_{II}z$, which at t_0 is coincident with the non-rotating system x_Iy_Iz and rotates with the same angular velocity ω_b about the z-axis (CC) as the ball.

At time t_1, the axis x_I has remained parallel to itself, while the axis x_{II} encloses the angle $\omega_b(t_1-t_0)$ with its position at t_0, and thus also with the axis x_I at t_1; further, OC encloses an angle $\omega_c(t_1-t_0)$ with x_I at instant t_1. Hence, from coincidence at t_0, the rolling axis OC has come at instant t_1 to enclose the angle $(\omega_c-\omega_b)(t_1-t_0)$ with the axis x_{II}, *i.e.* OC rotates about the z-axis relative to the $x_{II}y_{II}$-plant, and thus also relative to the ball, with angular velocity $\omega_c-\omega_b$.

Accordingly T_R (as defined for Case I), whose vector coincides with OC rotates with angular velocity $\omega_c-\omega_b$ about the z-axis relative to $x_{II}y_{II}$, and hence also relative to the ball. Thus the plane of T_R continually coincides with different diametral planes of the ball, and T_R causes angular accelerations in these planes. Therefore, at every instant, the ball rotates about a different rolling axis, the instantaneous axis of rolling. In this case, T_R will describe a complete circle in the $x_{II}y_{II}$-plane in the time interval $\tau_{II}=2\pi/(\omega_c-\omega_b)$, which means that each radius vector of the ball falling into this circle will coincide, at one instant during this time, with T_R, when it will represent the instantaneous axis of rolling.

In general, the occurrences in Case II, with $0<\omega_b<\omega_c$, can be represented as similar to those of Case I, but with a different overall system of reference which rotates about the bearing axis OO with angular velocity ω_b, and with $\omega_c-\omega_b$ substituted for ω_c in all the expressions derived for Case I (*see* Ref. 1, p. 204).

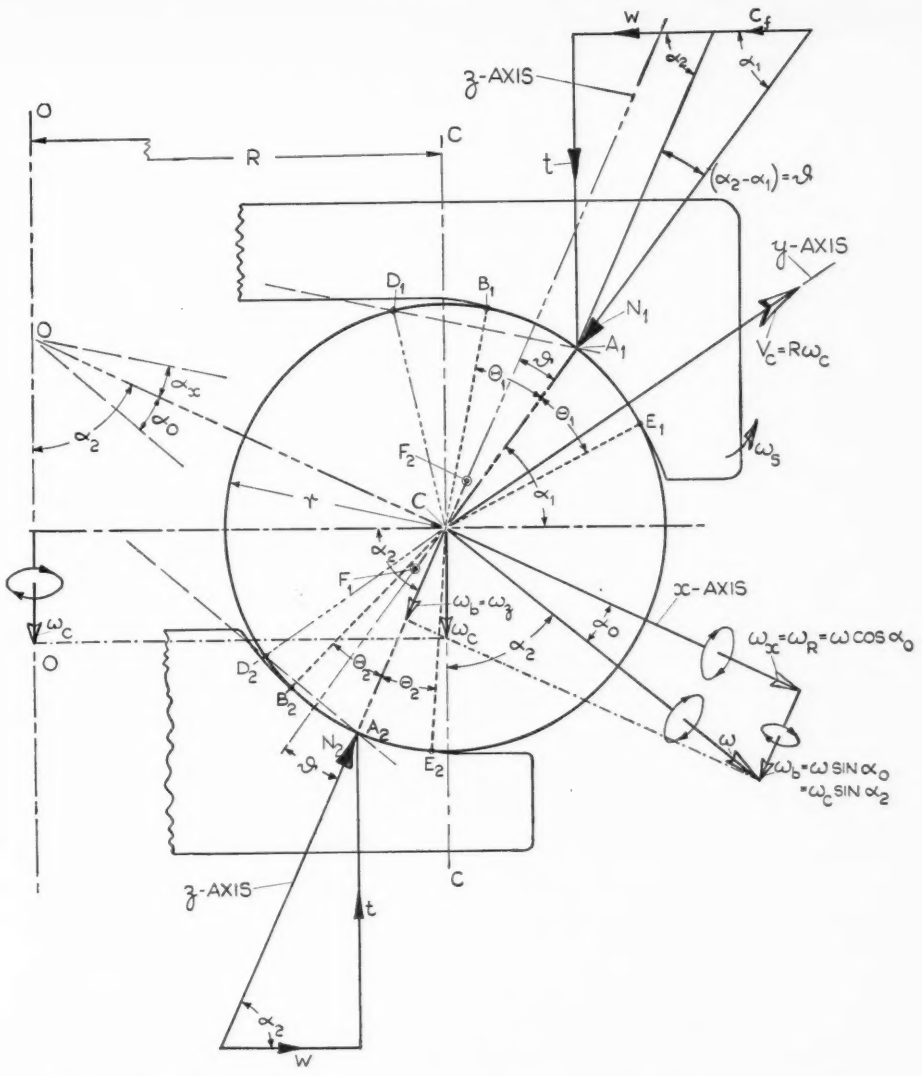

Fig. 5.—Part section through an angular contact ball bearing. The outer (upper) ring, which takes up the centrifugal force C_f, is the driving ring, the inner ring being stationary. Lines A_1CF_1 and A_2CF_2 defined by the positions of the centres of curvature F_1 and F_2 of the groove profiles, are referred to as the "constructed" axes of symmetry of the groove profiles.

In the same way as for Case I, following the axes x_{II} and y_{II} from their positions at instant t_0 when x_{II} coincides with T_R, the couple T_R will have components about axes x_{II} and y_{II} which vary with a sinusoidal oscillation of period $\tau_{II}=2\pi/(\omega_c-\omega_b)$, having a phase displacement of $\frac{1}{2}\pi/(\omega_c-\omega_b)$; similarly, the angular velocities

$\omega_{(x,0)}$ and $\omega_{(y,0)}$, about the axes x_{II} and y_{II} respectively, which T_R will have produced at instant t_0, are respectively given by

$$\int_{t_{(-3)}}^{t_0} T_R \cos\left[(\omega_c - \omega_b)t\right] dt - \int_{t_{(-3)}}^{t_0} T_{Fx}\, dt = I\left(\omega_{(x,0)} - \omega_{(x,-3)}\right). \quad . \quad (61)$$

and

$$\int_{t_{(-3)}}^{t_0} T_R \sin\left[(\omega_c - \omega_b)t\right] dt - \int_{t_{(-3)}}^{t_0} T_{Fy}\, dt = I\left(\omega_{(y,0)} \mp \omega_{(y,-3)}\right), \quad . \quad . \quad (62)$$

where $\omega_{(x,-3)}$ and $\omega_{(y,-3)}$ are the angular velocities of the ball about the x_{II}- and y_{II}-axes at time $t_{(-3)} = t_0 - \frac{1}{2}\pi/(\omega_c - \omega_b)$.

At time t_0 the ball has an angular velocity $\omega_{(x,0)}$ about the x_{II}-axis (the then instantaneous axis of rolling) and an angular velocity $\omega_{(y,0)}$ about the y_{II}-axis normal to it. These angular velocities will each reach maximum values at positions at which the respective components of T_R producing them are zero; after such positions they will be reduced by components of T_R acting in the opposite directions of rotation, until, having passed through zero, minimum values (*i.e.* maximum values in the opposite direction) are reached, and so on; *i.e.* the angular velocities about the x_{II}- and y_{II}-axes oscillate, but with period $\tau_{II} = 2\pi/(\omega_c - \omega_b)$ instead of with period $\tau_I = 2\pi/\omega_c$ as for Case I, and with phase displacement $\frac{1}{2}\pi/(\omega_c - \omega_b)$. The same applies to any other pair of orthogonal axes x and y in the $x_{II}y_{II}$-plane and rotating with the ball about the z-axis. These oscillations are denoted " pseudo-gyroscopic effect ".

Further, since each set of axes x and y also rotates with angular velocity ω_b about the z-axis, gyroscopic inertia couples $I\omega_x\omega_b$ and $I\omega_y\omega_b$ arise, which tend to rotate the ball about the x- and y-axes respectively. This produces oscillations of the angular velocities due to gyroscopic effect; these are additional to those already described, causing oscillations of a more complex nature.

In each circumferential position, a ball has not only an angular velocity ω_R about its instantaneous axis of rolling, coincident with T_R, but also an angular velocity ω_N about the diametral axis normal to OC and CC; these angular velocities oscillate in magnitude (since their axes are only instantaneous axes in the ball, they do not give rise to gyroscopic effects).

The combined oscillations of the angular velocities together with the occurrences relating to friction in the contact areas with the tracks (*see* Ref. 1, p. 219) will produce oscillations of the velocities of C in the tangential as well as in the radial directions of the path of the ball. Thus, for example, during a revolution of the centre about OO the velocity vector of the ball relative to the track in the radial direction (normal to its path) will reverse its direction several times, *i.e.* the ball will carry out several reciprocating motions relative to its groove. Several such motions during one revolution mean that each takes place in an extremely small time interval, giving high frequency impulses of the balls against the grooves; the magnitude of these impulses is twice the product of the ball mass and the relative velocity between ball centre and track (radially to the track), divided by the almost infinitely small time interval. Hence, the higher the speed of rotation of the bearing, the more frequent and the greater are these impulses. With their attendant high frequency variations of the stresses in the contact areas (both normal and tangential (friction) stresses) they are much more harmful than the load without such oscillations, and thus cause premature fatigue of the metal.

The same oscillations will cause reversals of the relative velocity between ball and cage (in the directions circumferential to the ball path); the velocity of the cage, which is also oscillating, is determined by the velocities of the other balls in the race,

the oscillations of which will be displaced in phase. This leads to periodic impulses of the ball against the cage, the more frequent and greater the higher the speed, causing great strain in the cage.

These phenomena occur similarly in angular contact ball bearings in which the angular velocity ω_b of the ball, now about the constructed axis of symmetry of the groove profile in the stationary track (*see* CA_2 in Fig. 5), is less than the angular velocity $\omega_c \sin \alpha_2$ of the friction couple from the tracks (equivalent to T_R) about this axis; this is so in bearings not constructed according to the Relations of the Dimensions. It must be stressed that these phenomena, due mainly to "pseudo-gyroscopic effects," occur under any magnitude of pressure forces on the ball, since they are caused mainly by the forces and their couples acting on the balls from the tracks, and can be prevented only by observance of the Relations of the Dimensions, which provide the ball motion of Case III, free from phenomena causing premature fatigue.

CASE III: In this case $\omega_b = \omega_c$ for an axial ball bearing; angle of contact $\alpha_2 = 90°$; $\omega_b = \omega_c \sin \alpha_2$ for an angular contact ball bearing; $0 < \alpha_2 < 90°$.

The motion is represented in Fig. 4 with reference to axes x_{III} and y_{III} rotating with angular velocity ω_c about the z-axis, and hence having no rotation relative to OC, coincident with x_{III} and velocity vector V_c, coincident with y_{III}.

One and the same diametral plane of the ball should always coincide with the rotating plane zV_c, where $V_c = r\omega_c$ and the z-axis is generally the constructed axis of symmetry of the groove profile in the stationary track (*see* CA_2 on Fig. 5). This is essential in order that T_R should act throughout in the same diametral plane of the ball, causing the rolling angular velocity ω_R about $OC(x_{III})$ normal to the plane zV_c which is now immovable relative to the ball (not an instantaneous axis). Further, when a constant shaft speed has been reached, T_R should only have to overcome the (very small) rolling resistance of the ball.

Thus, the motion must be such that:—

(*i*) the ball rotates with angular velocity $\omega_b = \omega_c \sin \alpha_2$ about its z-axis (A_2C in Fig. 5), which makes an angle $(90° - \alpha_2)$ with OO (*see* Ref. 1, p. 222);

(*ii*) the ball rotates about its rolling axis OC (x) (normal to the plane zV_c and immovable relative to the ball) with the rolling angular velocity $\omega_R = R\omega_c/r$; OC makes an angle α_2 with OO;

(*iii*) the ball has no angular velocity about its y-axis, coincident with V_c, *i.e.* $\omega_y = 0$. The expression "true rolling" used in Ref. 1 refers to the motion just described.

5. DESIGN EQUATIONS RELATING TO CONFORMITY

For trouble-free motion, the sums of all the couples acting on the ball about any axis through C must be zero at constant shaft speed.

i.e. $$\Sigma T_x = 0; \quad \Sigma T_y = 0; \quad \Sigma T_z = 0, \qquad . \quad . \quad . \quad . \quad (63)$$

where ΣT_x, ΣT_y and ΣT_z are the sums of all the moments about the axes x, y and z. In Figs. 5 and 6 (*a*), (*b*) and (*c*), x is the rolling axis OC, y coincides with the velocity vector V_c and z is the axis of symmetry of the groove profile in the non-driving track, A_2CF_2 in this case; the angular velocities of the ball about these axes are respectively $\omega_x = \omega_R = R\omega_c/r$; $\omega_y = 0$; $\omega_z = \omega_c \sin \alpha_2$.

In this way,

$$(\Sigma T_z)\omega_z = 0; \quad (\Sigma T_x)\omega_x = 0 \qquad . \quad . \quad . \quad . \quad (64)$$

which means that the energy input into the ball at the driving track plus the energy loss from the ball at the non-driving track equals zero.

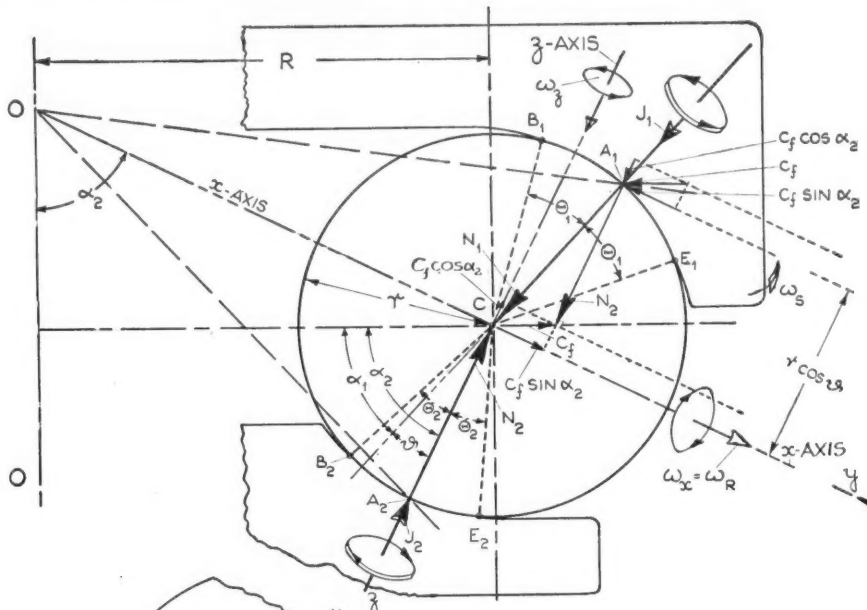

Fig. 6(*a*).

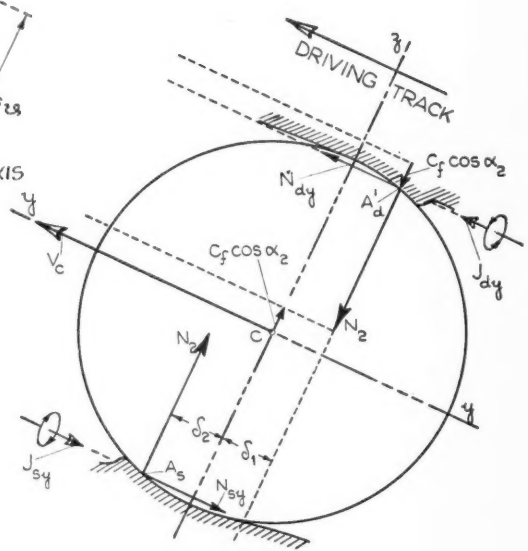

Fig. 6(*b*).

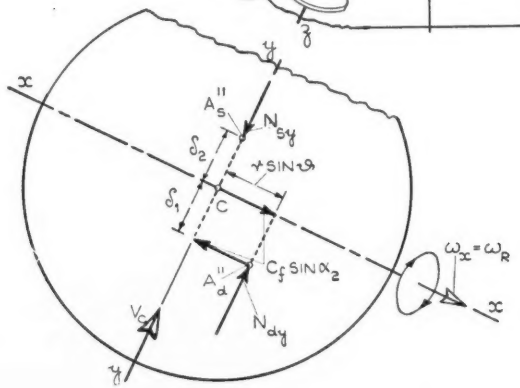

Fig. 6(*c*).

Fig. 6(*a*), (*b*) and (*c*).—Effects of indentations into the tracks. (The indentations are

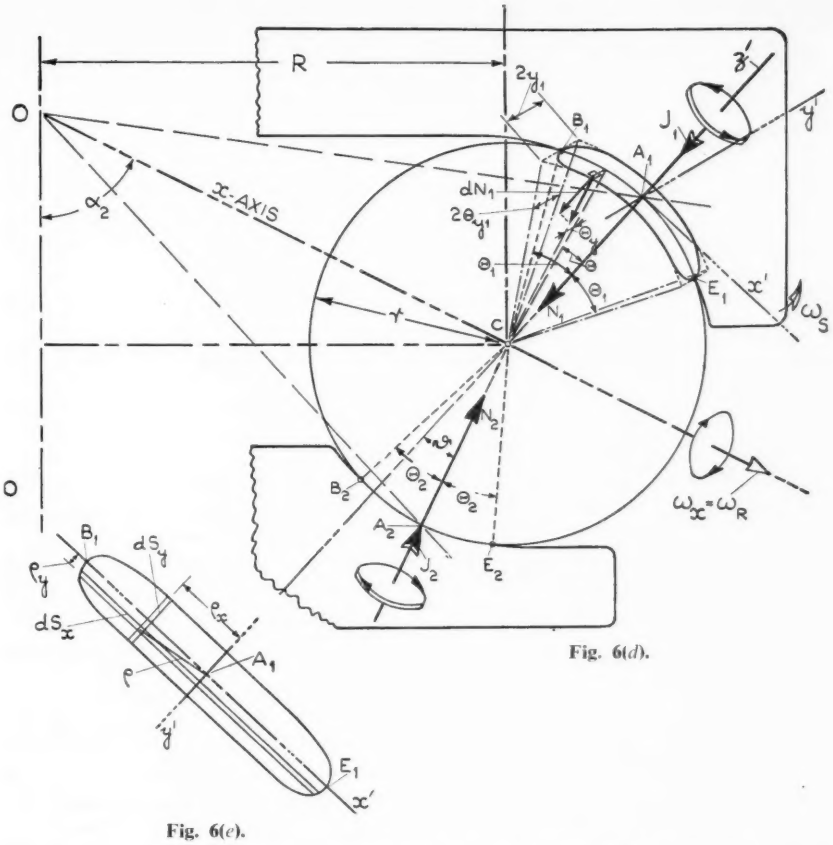

Fig. 6(*d*).

Fig. 6(*e*).

Fig. 6(*d*) and (*e*).—Contact area between ball and track. Fig. 6(*e*) shows the enlarged developed contact area between the ball and the driving track.

The forces and couples acting on a ball are now considered with reference to Figs. 5 and 6 (*a*), (*b*) and (*c*).

At constant shaft speed, the surface areas in contact on the driving track and on the ball have different angular velocities about A_1C. Thus there is a relative rotation between these two surface areas, about the axis A_1C, where A_1 is the instantaneous centre of the ball's motion with respect to the driving track; *i.e.* there is a relative velocity of sliding at each point between the surfaces in contact, except at A_1 (*see* Ref. 1, p. 233 *et seq*). This sliding causes equal and opposite friction forces forming a couple about A_1C, denoted by vector J_1 (since acting from the driving track). In the same way a friction couple arises about A_2C, which is denoted by vector J_2 (since acting from the stationary track) (*see* Fig. 6(*a*)). The vectors J_1 and J_2 enclose the angle ϑ (*see* the triangle of forces $A_1A_4A_5$ on Fig. 5).

Due to the indentations which a ball under load makes in its motion, the points of action A_1 and A_2 (*see* Fig. 6(*b*)) of the pressure forces N_1 and N_2 in the contact areas are displaced in the *y*-direction by small distances δ_1 and δ_2, to either side of the

xz-plane, to positions A_d and A_s respectively; the projections of A_d and A_s on to the zy-plane are A_d' and A_s'. Accordingly, the co-ordinates of A_d and A_s in the xyz-system are

$$x_d = r\sin\vartheta\,;\quad y_d = \delta_1\,;\quad z_d = r\cos\vartheta \qquad (65)$$

$$x_s = 0\,;\quad y_s = \delta_2\,;\quad z_s = -r. \qquad (66)$$

The z-components of N_1,

$$N_{1z} = N_2 + C_f\cos\alpha_2 \qquad (67)$$

acting at A_d and the z-component of N_2,

$$N_{2z} = N_2 \qquad (68)$$

acting at A_s are at distances δ_1 and δ_2 on either side of the xz-plane, and the x-component of N_1,

$$N_{1x} = C_f\sin\alpha_2 \qquad (69)$$

acting at A_d'' is at distance δ_1 from C (*see* Fig. 6(*c*)).

A further consequence of the indentations of the ball into the tracks are the forces N_{dy} and N_{sy} at points A_d and A_s respectively; they are parallel to the y-axis (V_c), in opposite directions and, as shown later, are equal.

Further, the vectors J_1 and J_2 will only be the projections on to the xz-plane of the vectors J_d and J_s of the actual friction couples, which pass through the instantaneous centres A_d and A_s respectively and through C.

Hence
$$\boldsymbol{J}_d = \boldsymbol{J}_1 + \boldsymbol{J}_{dy} \qquad (70)$$

and
$$\boldsymbol{J}_s = \boldsymbol{J}_2 + \boldsymbol{J}_{sy}. \qquad (71)$$

This means that J_1 and J_2 have remained the same, but that additional vectors J_{dy} and $-J_{sy}$, parallel to the y-axis, have arisen from the additional friction forces about A_d and A_s due to the additional forces N_{dy} and N_{sy}.

Finally, there is the centrifugal force C_f at the ball-centre, with components

$$C_{fx} = C_f\sin\alpha_2 \qquad (72)$$

and
$$C_{fz} = C_f\cos\alpha_2. \qquad (73)$$

At constant shaft speed

$$\Sigma X = 0;\ \Sigma Y = 0;\ \Sigma Z = 0, \qquad (74)$$

where ΣX, ΣY, ΣZ are respectively the sums of all the component forces in the x-, y- and z-directions. The moments acting on the ball are considered.

Consider first the moments about the x-axis:—

(*i*) Of the force N_{1z} acting at A_d, the part N_2 is at distance $\delta = \delta_1 + \delta_2$ from N_2 acting at A_s (*see* Fig. 6(*b*)), and forms with this the couple $T_{x1} = -N_2\delta$ against rolling.

(*ii*) The part $C_f\cos\alpha_2$ of N_{1z} is distant δ_1 from $C_{fz} = C_f\cos\alpha_2$ at C, and hence forms with it the couple $T_{x2} = -\delta_1 C_f\cos\alpha_2$.

(*iii*) The vector of the friction couple J_d at A_d (*see* Fig. 6(*a*)) causes (*see* equation (70)), the moment $T_{x3} = -J_1\sin\vartheta$, all three moments acting against the rolling angular velocity and forming the rolling resistance.

(*iv*) Since no other forces have components in the y-direction, from condition (74),

$$N_{dy} = -N_{sy}, \qquad (75)$$

These two forces at A_d and A_S have the arm $r(1+\cos\vartheta)$, and hence form the couple $J_{z4}=N_{dy}r(1+\cos\vartheta)$, to overcome the rolling resistance.

Hence $$\Sigma T_x = -J_1\sin\vartheta - \delta N_2 - \delta_1 C_f\cos\alpha_2 + N_{dy}r(1+\cos\vartheta)=0. \quad . \quad . \quad (76)$$

Considering the moments about the z-axis:—

(*i*) The friction couple J_d at A_d forms about the z-axis (*see* Fig. 6(*a*) and equation (70)) the couple $T_{z1}=J_1\cos\vartheta$.

(*ii*) The friction couple J_S at A_S, opposing J_d, forms (*see* Fig. 6(*a*) and equation (71)) the couple $T_{z2}=-J_2$.

(*iii*) The force N_{1x} at A_d has the arm δ_1 with the x-component of C_f at C (*see* Fig. 6(*c*)), hence forming the couple $T_{z3}=-\delta_1 C_f\sin\alpha_2$.

(*iv*) The equal and opposite forces N_{dy} and N_{Sy} at A_d and A_S having arm $r\sin\vartheta$ form the couple, in the direction of J_d, $T_{z4}=N_{dy}r\sin\vartheta$.

Hence $$\Sigma T_z = J_1\cos\vartheta - J_2 - \delta_1 C_f\sin\alpha_2 + N_{dy}r\sin\vartheta = 0. \quad . \quad . \quad . \quad (77)$$

Considering moments about the y-axis, including the gyroscopic inertia couple:—

(*i*) Since the vectors of the friction couples J_d and J_S pass respectively through A_d and A_S and through the C (*see* equations (70) and (71)), they have opposite components J_{dy} and J_{Sy} about the y-axis. These, with J_{Sy} positive, form the moment $T_{y1}=J_{Sy}-J_{dy}$.

(*ii*) Only the x- and z-components of the forces acting on the ball (as shown on Fig. 6(*a*)) can form couples about the y-axis. However, the x- and z-components acting at A_1 form the resultant N_1 passing through the y-axis, and the x- and z-components acting at A_2 form N_2 passing through the y-axis, while C_f acts through C. Hence these three resultant forces acting through the y-axis form no resultant couple about the y-axis and $T_{y2}=0$.

(*iii*) The gyroscopic inertia couple (from equation (49)), acting in the positive direction, forms the moment $T_{y3}=I\omega_c^2\sin(\alpha_2-\alpha_0)\sin\alpha_2/\sin\alpha_0$.

(*iv*) Since $T_{y2}=0$ and $J_{Sy}-J_{dy}\simeq 0$ (the proof is omitted), the remaining gyroscopic inertia couple, tending to produce a rotation about the y-axis, results in friction forces $N_1\mu_1$ and $N_2\mu_2$ at A_d and A_S respectively; the forces are in planes parallel to the xz-plane and form moments about the y-axis (denoted vectorially T_{Fy1} and T_{Fy2}) opposing the gyroscopic couple.

Hence $$\Sigma T_y = \left(I\omega_c^2\sin(\alpha_2-\alpha_0)\frac{\sin\alpha_2}{\sin\alpha_0}\right) - (T_{Fy1}+T_{Fy2}) + (J_{Sy}-J_{dy}) = 0. \quad (78)$$

Neglecting the couple $(J_{Sy}-J_{dy})$ gives the limiting condition (55) derived in Section 3.

To obtain an equation for the Relations of the Dimensions from (76) and (77), J_1 and J_2 are written

$$J_1 = \int_0^{S_1} \mu p_{m1}\,dS\,\rho \quad . \quad . \quad . \quad . \quad . \quad (79)$$

$$J_2 = \int_0^{S_2} \mu p_{m2}\,dS\,\rho \quad . \quad . \quad . \quad . \quad . \quad (80)$$

where p_{m1} and p_{m2} are the mean pressures in the contact areas S_1 and S_2 about A_1

and A_2 respectively, dS are elements of area with radii ρ about A_1C and A_2C respectively.

The mean pressure p_{m1} in the contact area S_1 about A_1

$$p_{m1} = \frac{1}{4\int_0^{\theta_1}\int_0^{\theta_{y1}} r\cos\theta\, d\theta\, r\cos\theta_y\, d\theta_y}$$

for substitution in

$$J_1 = 2\int_0^{S_1/2} \mu p_{m1}\, dS_y\, \rho_x - 2\int_{S_1/2}^{0} \mu p_{m1}\, dS_x\, \rho_y$$

where (*see* Figs. 6 (*d*) and (*e*)) for the contact area S_1

$$dS_y = (2r\theta_{y1})\, rd\theta;\ dS_x = (2r\theta_1)\, rd\theta_y;\ \rho_x = r\sin\theta;\ \rho_y = r\sin\theta_y .$$

Taking into account that θ_{y2} is very small and that $2r\theta_{y1} = \delta_1 + \delta_2 = \delta$, gives the following value for J_1, and similarly, since $2r\theta_{y2} = \delta_2(1 + \delta_2/\delta_1)$, the value for J_2.

It can be shown that

$$J_1 = N_1\mu\sigma_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (81)$$

$$J_2 = N_2\mu\sigma_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (82)$$

where
$$\sigma_1 = r\tan\left(\frac{\theta_1}{2}\right) + \frac{\theta_1}{\sin\theta_1}\frac{(\delta_1+\delta_2)}{4} \quad . \quad . \quad . \quad . \quad (83)$$

and
$$\sigma_2 = r\tan\left(\frac{\theta_2}{2}\right) + \frac{\theta_2}{\sin\theta_2}\frac{\delta_2}{4}\left(1+\frac{\delta_2}{\delta_1}\right) \quad . \quad . \quad . \quad (84)$$

where θ_1 and θ_2 (*see* Figs. 5 and 6(*d*)) are the angles subtended at C by the half-lengths of contact area $A_1B_1 = A_1E_1$ and $A_2B_2 = A_2E_2$.

From (76) and (77), (83) and (84), and substituting for N_1 and N_2 in terms of C_f and α_2 and ϑ from the triangle of forces $A_1A_4A_5$ on Fig. 5,

$$\left.\begin{aligned}\frac{\sin(\alpha_2-\vartheta)}{\sin\alpha_2\cos\vartheta}\left[1-\frac{\delta\sin\vartheta}{\sigma_2(1+\cos\vartheta)}\right] = \frac{\sigma_1}{\sigma_2}\left[1+\frac{\tan\vartheta\sin\vartheta}{1+\cos\vartheta}\right] - \\ -\frac{\delta_1}{\sigma_2}\frac{\tan\vartheta}{(1+\cos\vartheta)}\left[1+\frac{\sin(\alpha_2-\vartheta)}{\sin\alpha_2}\right]\end{aligned}\right\} . \quad (85)$$

For speeds other than extremely high ones, the term with $\delta_1\tan\vartheta$ becomes negligible, leaving a simplified equation.

6. RELATIONS OF THE DIMENSIONS FOR ANGULAR CONTACT BALL BEARINGS

The mathematical formulation of conditions for trouble-free motion in an angular contact ball bearing results in the following system of equations (*see* also Ref. 1), representing the Relations of the Dimensions as functions of ranges of loading and speed:—

$$\frac{\sin\alpha_2}{\tan\alpha_0} = \frac{R}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad (86)$$

$$\tan\frac{\vartheta}{2} = \frac{k}{1+k}\tan\alpha_0 \quad . \quad . \quad . \quad . \quad (87)$$

$$\frac{\sin \alpha_x}{\sin \alpha_0} = \frac{\cos (\alpha_x + \vartheta)}{\cos \alpha_0} \quad . \quad . \quad . \quad . \quad . \quad (88)$$

$$\frac{\sin \alpha_2 \sin (\alpha_2 - \vartheta) MRn}{\sin \vartheta} = \frac{P_t}{\omega_c^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (89)$$

$$\left.\begin{aligned} \frac{\sin (\alpha_2 - \vartheta)}{\sin \alpha_2 \cos \vartheta}\left[1 - \frac{\delta \sin \vartheta}{\sigma_2 (1+\cos \vartheta)}\right] &= \frac{\sigma_1}{\sigma_2}\left[1 + \frac{\tan \vartheta \sin \vartheta}{(1+\cos \vartheta)}\right] - \\ &\quad - \frac{\delta_1}{\sigma_2} \frac{\tan \vartheta}{(1+\cos \vartheta)}\left[1 + \frac{\sin (\alpha_2 - \vartheta)}{\sin \alpha_2}\right] \\ \sigma_1 &= r \tan\left(\frac{\theta_1}{2}\right) + \frac{\theta_1}{\sin \theta_1} \frac{(\delta_1 + \delta_2)}{4} \\ \sigma_2 &= r \tan\left(\frac{\theta_2}{2}\right) + \frac{\theta_2}{\sin \theta_2} \frac{\delta_2}{4}\left(1 + \frac{\delta_2}{\delta_1}\right) \end{aligned}\right\} \text{ see equations (85), (83), (84)}$$

with the limiting conditions

$$\theta_2 \leqslant 2\alpha_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (90)$$

$$\theta_1 \leqslant 2(\alpha_x + \vartheta) \quad . \quad . \quad . \quad . \quad (91)$$

and from Section 3

$$\left.\begin{aligned} Mrn\left(\frac{R}{r} - \cos \alpha_2 \sin \alpha_2\right) \sin (\alpha_2 - \vartheta) &\leqslant \frac{P_t \mu_S}{0.4 \omega_c^2} \\ \text{where} \qquad \omega_c &= \omega_S \frac{R + r \cos (\alpha_2 - \vartheta)}{R(\cos \vartheta + 1) + r \sin \alpha_2 \sin \vartheta} \end{aligned}\right\} \text{ see equations (55) and (56)}$$

and, from the Theory of Elasticity of H. Hertz

$$r_{F1} = f_{(1)}(\theta_1, r, R, P_t/n, \ldots .) \quad . \quad . \quad . \quad (92)$$

$$r_{F2} = f_{(2)}(\theta_2, r, R, P_t/n, \ldots .). \quad . \quad . \quad . \quad . \quad (93)$$

These Relations of the Dimensions are 10 main equations and three limiting conditions, for 16 quantities, of which some may be further limited by other conditions. For example the minimum value of r may be limited by considerations of maximum stress, or R by space considerations.

Apart from the variation of P_t and ω_S permitted by the ratio P_t/ω_c^2 in equation (89), the three limiting conditions (55), (89) and (90) allow three quantities to vary independently within the limits set by them.

Thus, for a bearing, whose geometry in the unloaded state is determined by R, r, r_{F1}, r_{F2}, α_2 and ϑ, it is seen that P_t and ω_S, with their dependent quantities, may vary as follows:—

(*i*) P_t/n, and hence ϑ, may vary for the same ball in different positions in the circumference, within the limits set by the conditions.

(*ii*) P_t/n may vary by alteration of the external load itself within the calculated limits.

(*iii*) ω_S, and hence ω_c and C_t and the angles, may vary within calculated limits.

Therefore, a bearing constructed in accordance with the Relations of the Dimensions is applicable for the following cases:—

(*i*) axial pressure force components t differing between maximum and minimum values for balls in different positions in the circumference, *i.e.* for an eccentric axial load, or for radial load combined with axial load.

(*ii*) the external load as a whole varies.

(*iii*) the shaft speed varies in operation.

(*iv*) any combinations of (*i*), (*ii*) and (*iii*) within the ranges calculated

In cases such as, for example, an angular contact (double) bearing under pure radial load, when the balls move without the control of both tracks for a large part of their circuit, and it is desired that the Relations of the Dimensions should apply in any circumferential position, this can be done by means of the Double Angular Contact Ball Bearing construction indicated in Ref. 1 and treated fully in *Machinery Lloyd*, Overseas Ed., 13th October, 1951. Even under a purely radial load this supplies substantially equalised axial pressure force components on balls in all circumferential positions, without pre-loading.

7. CONCLUSIONS

In bearings not constructed according to the Relations of the Dimensions, the angular velocities about different polar axes, which a ball attains in its circular motion, oscillate because of a hitherto unrecognised manifestation denoted " pseudo-gyroscopic effect," apart from the minor influence of gyroscopic effect. These oscillations, in combination, produce, besides periodic impulses of the balls against the cage, periodic impulses of high frequency of the ball against the track grooves, with high-frequency oscillations of the stresses in the contact areas between balls and tracks (over and above the stress variation due to a ball passing a given spot on a track). The impulses cause premature fatigue, as a function of the speed, and lead to the present limitations on maximum speeds and life. A motion free from oscillatory effects is obtained in a bearing constructed in accordance with the Relations of the Dimensions.

Analysis of the equations and limiting conditions of the Relations of the Dimensions shows that, while leading dimensions such as pitch-circle radius are open to choice, a particular bearing constructed according to Relations of the Dimensions is applicable over ranges of speed and loading given at the end of Section 6.

REFERENCE

1. FRENKEL, M. S. (1946). Ball and Taper Roller Bearings. *Journal of the Royal Aeronautical Society*, March 1946.

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CORRESPONDENCE

G. W. Smith and J. B. Rea, in their paper "Aeroplane Tail Loads for Longitudinal Manœuvres" (October 1952 JOURNAL), describe the application of control theory to the calculation of the tail loads due to arbitrary elevator deflection. The notation used in the paper is formidable and may prevent those who are unfamiliar with the subject from making the attempt to understand it. The avoidance of the double suffix is one of the main blessings of the British stability notation and it may be of interest to point out how this principle has been applied to the definition of aircraft transfer functions as used at the Imperial College.

The transfer function, say Y, is essentially a ratio of output to input of a part of a control system—or aircraft. Its form will depend on the manner in which the output and input are expressed. In the paper by Smith and Rea they are written as "steady side" sinusoidal quantities and Y becomes $Y(i\omega)$, the circular frequency being ω and $i=\sqrt{(-1)}$. Had they been written in operational form, the transfer function would have been $Y(D)$ or $Y(p)$, D being d/dt and p the auxiliary variable of the Laplace transform as used in response calculations for linear systems. In practice the nature of the argument of the function is obvious from the circumstances and need not be made to clutter up the symbol. Nor is there any need to write the letter Y or alternative forms of it. Consequently, we replace the symbol $(\text{T.F.})_{w/\delta}$ by w_η to represent the w response of an aircraft to the application of elevator deflection η and so on. The fastidious may wish to place a bar like $\overline{w}_\eta$ to indicate the operational or vector nature of the symbol.

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19th November 1952.

REVIEWS

In the October Journal (page 804*) the price of the book "Helicopter Analysis," Chapman & Hall Ltd., was incorrectly given as* 53*s.* 6*d. The price is* 60*s. net.*

The following are reviewed:—

Mechanics of Vibration.
Air Navigation—Theory and Practice.
Handbook of Aerial Mapping and Photogrammetry.
Development of the Guided Missile.
The A.B.C. of Model Aircraft Construction.
Principles and Practice of Aviation Medicine.
The Fated Sky.
Khaki and Blue.
Aircraft Engines of the World 1952.
Aeronautical Engineering Index.
Air Transportation Management.
The Observer's Book of Aircraft.
Aeroplanes and Aero-Engines.
Dunlop Aviation Equipment Manual.
Flames in the Sky.
Escape—or Die.
The Crowded Hours.
Faith is a Windsock.
Pioneer Pilot.

MECHANICS OF VIBRATION. Holger M. Hansen and Paul F. Chenea. John Wiley and Sons, New York. Chapman and Hall, London. 1952. 413 pp. Index. $8.00 net.

This latest addition to the literature of mechanical vibration is intended primarily as a text-book for the use of students who have had a groundwork of instruction mathematics and elementary dynamics. The two authors—both from the Department of Engineering Mechanics at the University of Michigan—state that their aim has been to present the fundamentals of vibration theory in a manner readily understood by the undergraduate and yet at the same time on a plane acceptable to the graduate student. The treatment throughout is painstaking, and explanations are given with much attention to detail. A commendable feature of the volume is that it is extensively provided with clear explanatory diagrams. Sets of exercises to be worked out by the student are also included, and the answers are given at the end of the book.

The book has not been produced specially for aircraft engineers, and in fact it contains no references to aircraft vibrations. Nevertheless it covers much of the basic ground needed for the training of an engineer in vibration analysis, and for this reason it should be a useful help to the aircraft industry.

The text, following an introductory chapter concerned with fundamental definitions, is divided into three parts. Part I is devoted to a discussion of the properties of linear undamped and damped oscillatory systems with a single degree of freedom. The student is here introduced to free and forced vibrations, to the phenomenon of resonance, and to the conditions of energy balance. Systems with two or more freedoms are treated in Part II. The subjects covered in this section include the use of generalised coordinates and Lagrange's equations, vector methods and the concept of impedance, and the treatment of systems composed of elements arranged in series or parallel by the so-called mobility method. One chapter is devoted to a description of two representative methods for the numerical solution of the frequency equation. Part III, comprising three chapters, is concerned with special topics. One of these chapters is devoted to the oscillations of simple continuous systems such as taut strings, and elastic beams and shafts. Another discusses transient motions and the response of systems to forces represented by step functions. The final chapter relates to the oscillations of simple non-linear systems with a single freedom.

The standard of reproduction is good, and proof correction has been attended to carefully.

AIR NAVIGATION—THEORY AND PRACTICE. E. Brook Williams and W. J. V. Branch. Sir Isaac Pitman and Sons Limited, London. 1952. 644 pp. 372 figures. 55s. net.

Neither by first impressions nor on closer acquaintance will the disciples of orthodoxy be disturbed by this latest book on navigation; by the same token it may also be said that the practising navigator is unlikely to be inspired. It is maintained in the preface that "The object of most forms of tuition . . . is to pass an examination" and it will be generally agreed that in meeting the requirements for licences and especially as a basis for study by those who must, in part, be self-taught, this book will serve admirably. The exposition is generally lucid, diagrams are numerous, there are many worked examples and typographical setting is in no sense cramped.

While recognising that measure of permanence which the theoretical approach both bestows and imposes, it might have been expected that evolution would have wrought some change of emphasis. Many readers will be disappointed to find the whole science and application of radio and radar contained within about fifty pages—a fraction of the space allotted to either mathematics, astronomy or magnetism. Flight planning is accorded a modest but very useful concluding chapter. There is no special consideration of such navigational problems as arise in high-speed flying where even pure theory demands notice of the rhumb-line correction in bubble sextant observations and where, as a very practical point, the normal astrodome must be eliminated.

One is conscious of a tendency to oscillate between the minutely detailed and the frankly superficial in an attempt to be comprehensive. A somewhat apologetic introduction to "Tides" is unlikely to be comprehensible although a little expansion might have made it so. Again, after discussing gyroscope principles there is no mention of the errors to which gyro instruments are subject during and after turning flight. The omission of practical data on important systems is the less excusable when space is devoted to unedifying references to undeveloped ideas like the light-weight navigation computer—for some reason amongst the radio aids.

While the book may have little of novelty for the trained man the basic material—so thoroughly covered—is still the good earth in which the budding navigator must be rooted. There is no doubt that in spite of its appreciable bulk and price it will find wide acceptance as a self-contained manual of instruction.

HANDBOOK OF AERIAL MAPPING AND PHOTOGRAMMETRY. Lyle G. Trorey. Cambridge University Press. 1952. 180 pp. with diagrams, tables and photographs. 30s. net. *Second Edition.*

This is the second edition of "Handbook of Aerial Mapping" published in 1947 and described as "a book for the man who wants to make maps from air photographs . . . a book for the drawing office, a manual, not a text-book." The only additional section is a five-page Appendix giving details of the Kelsh plotter, a projection-type instrument with several ingenious features, including a new system of illumination, and a new method of compensation for sources of optical error. The author has corrected misprints and errors and added notes referring to latest knowledge.

DEVELOPMENT OF THE GUIDED MISSILE. Kenneth W. Gatland. A *Flight* publication. London. 1952. 133 pp., illustrated. 10s. 6d. net.

Much of this booklet is devoted to unguided rocket missiles and to projects of vehicles for space flight. Of the rest, scarcely any information is given which would be additional to treatises published three years ago. This deficiency, as the author justly claims, is due to security restrictions (which now withhold formerly "de-classified" material, including German work done before 1945).

Today, the design of a propelled missile has ceased to be a basic problem, but the perfection of reliable guide-control devices which give protection against interference, unintentional and intentional, is still beset with fundamental difficulties. This is indeed the crucial aspect regarding strategical application and tactical use of guided missiles. Unfortunately, the author has failed to make this point quite clear, and therefore arrives at unrealistic conclusions.

There are a number of points in which the reviewer cannot agree with the author. For example, the conception of the design ideas incorporated in the German V.2 rocket were due to H. Oberth (and not to W. von Braun and his Peenemunde staff). Robots cannot decide wars, and it is, therefore, pessimistic to imply that, because of the existence of long-range rockets, the devices of attack have outpaced the means of defence. Regarding air-to-air rockets, the problem of the missile size is important: small missiles cannot be guided and even the incorporation of proximity fuses is likely to result in one-shot "air-torpedoes."

The substance of the book was originally published in a series of articles in *Flight*, but the manuscript has been fully revised and a new Introduction reviews the problems of defence against the long-range supersonic rocket. The chapter headings are: The New Armament, Air-to-Air Missiles, Problems of the Supersonic Rocket, Rockets for High-Altitude Research, Space-Satellite Vehicles and Interplanetary Flight. An Appendix contains tables of data listing more than 80 guided missiles.

In view of the scarcity of information of the subject, the booklet will be of benefit to anyone needing introduction into the sphere of rocket missiles and devices for space travel, but for a serious study, references to more specialised literature would have been useful.

THE A.B.C. OF MODEL AIRCRAFT CONSTRUCTION. F. Callon. Model Aeronautical Press Ltd. Watford, Herts. 1952. 96 pp. Illustrated. 5s. net.

The difficulties facing beginners in many hobbies, particularly model making, would seem to vary in proportion to the enjoyment which may be obtained from the finished article. Although the demands made upon the skill and patience of the aeromodeller are as great as those made upon other modellers, the final reward for his pains is by no means assured. Some errors in construction may not come to light until the first (and possibly last) flight of the beginner's first (and possibly last) model.

In writing this excellent guide to elementary model aircraft construction, the Reverend F. Callon has clearly had these difficulties in mind. Emphasising care and patience from the start, the author gives his reader a programme of model building which might well lead to a lifetime's devotion to the hobby, with the dice heavily loaded in favour of successful flying throughout. Complete step-by-step instructions are given for building and flying "solid" gliders, "built-up" gliders and rubber-powered models. Of particular note from the viewpoint of the novice are the chapters on materials, tools, soldering, flying technique and repairs.

The book is well illustrated with drawings and photographs and contains a glossary of Aeromodelling Terms.

PRINCIPLES AND PRACTICE OF AVIATION MEDICINE. Harry G. Armstrong, M.D., F.A.C.P., Surgeon General U.S.A.F. Bailliere, Tindall & Cox Ltd. 1952. 471 pp. and Index. 57s. 6d. net. *Third Edition.*

Armstrong, in his fully revised third edition, has kept abreast of his subject since the first publication of "Aviation Medicine" in 1939. Although the early chapters remain virtually unchanged, the latter half of the book has been almost entirely rewritten, so that advances made during the war years have now been incorporated, together with some references even to the Korean campaign.

His general style of writing is both easy and interesting and the layout of the volume very concise. Particularly noteworthy are the headings of the chapters with their large Arabic numerals for easy reference.

For all those having particular interest in Aviation Medicine this volume can be highly recommended as an up-to-date reference; such aspects as altitude, velocity and pressurisation all receive careful consideration.

The General Practitioner of today receives an increasing number of enquiries from his patients as to the advisability, under certain conditions, of making journeys by air. This aspect is touched on, but rather too lightly, in the chapter on Air Rescue and Air Evacuation. The subject matter is actually to be found in this book, but could, it is considered, be set out in a more practical manner for easy reference by the busy practitioner.

This is a minor criticism, and otherwise the field has been covered with both sincerity and clarity.

THE FATED SKY. Air Chief Marshal Sir Philip Joubert de la Ferté. Hutchinson. London. 1952. 270 pp. Index. 18s. net.

Few autobiographies have been so unobtrusively phrased as this story of Sir Philip's life, beginning with childhood days in India, thence to Woolwich as a Cadet, with an early diversion to flying, and so to his career in the R.F.C. and R.A.F., ending with his retirement in October, 1945. It would be difficult to judge from this modest book that by his courage, ability and personality the author had earned distinction in two world wars and had done much to shape the destiny of the Royal Air Force in the years between. Indeed this book is written with such restraint for the feeling of his colleagues, and with such little criticism or comment, that it becomes a somewhat colourless story except when describing eastern countries, whereas it could well have been a forceful and brilliant history. The difficulty is to see living history as an entity when one has been immersed in a formative part. It is as though a single coloured fragment of the kaleidoscope overwhelms by its personal importance the complex pattern of the rest.

What Joubert does is to give hardly more than a personal catalogue of his service appointments, with something of their aim and scope, but reveals only a very little of his impact on their purpose. Thus his early belief in blind flying aids foreshadows his later and important association with R.D.F. developments, but nevertheless the fascinating story of Radar is barely unfolded. Yet had he wished, the author could have given a most interesting perspective. Similarly, his description of important events is somewhat disappointing, and none more so than the almost passing reference to the escape of the German battleships from Brest while he was A.O.C. Coastal Command. It was a disheartening event to the British, and many sensed a mishandling of the situation somewhere in the organisation of interception. Yet Sir Philip Joubert, with a fine impartiality, dismisses it broadly as due to "insufficient resources."

From occasional idiosyncrasies of expression which have managed to escape his self-imposed censorship it is just possible, in conjunction with the frontispiece photograph, to envisage the author's personality, but it is quite impossible to gain insight of the many famous and brilliant men with whom he has associated in these long eventful years. This can hardly be for the reason given in the title quotation taken from *All's Well That Ends Well.*

KHAKI AND BLUE. Colonel R. Sherbrooke-Walker. The Saint Catherine Press Ltd. 1952. 135 pp. Illustrated. 10s. 6d. net.

This is the story of the ground defence of our airfields and radar sites in the Second World War and how the R.A.F. Regiment was formed to take over these duties from the Army. By September 1939 the threat from low-flying aircraft, airborne attack and sabotage had been realised, to which was added the 1940 lesson of what armoured forces could achieve in land warfare. After Dunkirk, it was clear that if the enemy could secure a bridgehead on our coast, his armoured forces would move rapidly inland, and one of their early objectives would be the capture of our airfields.

In fulfilling its responsibility for these important defence duties the Army "produced a heterogeneous assortment of military detachments. Old soldiers, young soldiers and machine gunners were dispersed over the more important airfields to the annoyance of their own commanding officers who wanted them for training." As the German invasion threat gradually receded, the Army naturally wanted all their fit troops to form a field force for future overseas

operations, with the older men taking over static guard duties. After many talks between the two Services it was agreed that the R.A.F. should form its own Ground Defence units. From these early "soldiers in blue," and after much tribulation, there was ultimately evolved that smart and enthusiastic corps, the R.A.F. Regiment. The official date of its birth was 1st February 1942.

Colonel Sherbrooke-Walker had served in the R.F.C. in the 1914/18 War and had seen something of the small, well-disciplined force of regulars in peace time by visits to their annual displays. As an Army Officer he served with the R.A.F. from 1940 to 1945. His ground defence duties took him to many stations fully engaged in operations against the enemy, and he goes to some lengths to criticise the comparative untidiness and lack of discipline of the pilots. The fact that many of these were reservists or keen volunteers, so ably filling the gaps left by grave losses among the regulars, is not mentioned—nor is the spirit of all ranks that carried us through those hectic days of 1940.

To find no reference to the R.A.F. Regiment in its many service actions is strange. No mention of incidents of the 1943 N.W. African campaign; of how the Regiment, in face of strong enemy forces, re-established the line in mountainous coast country near Cap Serrat from which the Army had withdrawn. All done at the personal direction of the late A.V.M. (then Group Captain) David Atcherley, so that his forward radar station, virtually in enemy territory, would enable his night-fighters to operate against the main enemy supply route from Italy to Africa. No mention of squadrons of the Regiment in 1945 being the first Allied troops to force their way into Denmark, in spite of S.S. Divisions and armoured vehicles. And so the fine record of the R.A.F. Regiment in action in France, Africa, Italy, Malaya and other campaigns still remains untold.

AIRCRAFT ENGINES OF THE WORLD 1952. Paul H. Wilkinson. Pitman. London. 1952. 320 pp., including index. Illustrated. 50s. net.

This new edition, which is well up to the standard of previous editions, contains 139 pages of description and data on jet engines, 138 pages similarly on reciprocating engines, plus data on aviation fuels and lubricants and engine index. The engine data is tabulated in the standard manner of earlier editions and is comprehensive in detail.

Of 64 turbine engines now listed, 16 are new and 39 revised in this issue. The new British engines are the Armstrong Siddeley Viper jet and the Bristol Phoebus research jet. Six Russian turbine engines are listed, five of which are developments of German designs, including the Russian version of the B.M.W.028 turbo-prop; the sixth is a copy of the Rolls-Royce Nene.

Of 66 piston type engines, only three are new to the publication. One of these is the composite Napier Nomad. Data on 37 of the listed types is revised, while 26 engines are neither new nor require revision.

In addition to this information, which relates primarily to engines which have reached production status, there is a useful review of the known technical developments on aircraft turbine and reciprocating engines during the year throughout the world. This section is extended to engine accessories.

The latest edition shows that the book continues to increase in value as a source of data and ready reference for those connected with the technical side of the aero-engine industry.

AERONAUTICAL ENGINEERING INDEX 1951. Institute of the Aeronautical Sciences. New York. 1952. 203 pp. $3.00 to members. $5.00 to non-members.

The aeronautical librarian's "unpaid assistant" for 1951 has appeared at last and inquirers will receive more recent information in answer to a much greater percentage of their questions. The preface gives some idea of the vast amount of literature that appears, bearing on aeronautics, with such figures as more than 300 periodicals and reports series reviewed giving rise to 4,500 entries. In addition, 496 books are reviewed or "noticed." When one adds the fact that 60 per cent. of the material carries a brief abstract, it will be seen that this Index is invaluable. 1951 is the fifth in the series and each year sees some improvement in layout, but it is a pity that in the current number the editors have "dropped" the alphabetical index which was included in 1950. This, however, is a sheer cavil since the Subject Classification—Detailed Outline should be workable by the newest addition to the staff and, if the author is known, the index at the end of the book makes it even easier.

AIR TRANSPORTATION MANAGEMENT. Joseph L. Nicholson. John Wiley & Sons Inc. 1951. 446 pp. Illustrated. $6.50 net.

Books about Air Transport appear so rarely in this country that American publications in this field are of greater relative importance to the British student than are foreign text books on most other subjects. In the circumstances it is fortunate that there is no shortage of American books on Air Transport and that a fair selection of those published across the Atlantic manage to find their way over here every year.

Unfortunately many of these books are of limited value to the serious student and one hesitates to recommend the spending of precious dollars on anything which is not good value for money. "Air Transportation Management" is an exception. In spite of the implied restricted treatment of its rather misleading title, this book is an exceptionally comprehensive survey of the air transport industry in the United States. It is written by a consultant and lecturer on the economics of transport at Temple University who has been connected with the airline industry since it earliest beginnings in the United States in 1925.

After explaining the significance of Air Transport and outlining its growth in the United States in two introductory chapters, Mr. Nicholson gives an adequate, if superficial, survey of the American domestic, international and local service picture backed by liberal use of some of that vast mass of C.A.B. statistical data which is so readily available to the American researcher. This is followed by chapters devoted to such subjects as "Airways and Airports," "Safety, Meteorology and Communications," and "Airline Organisation and Management," in all of which these and similar branches of the subject are discussed at length and the relevant statistics interpreted. Special emphasis is given to the—from the American point of view—unusually close interest of the Government in the industry. Thus, the functions of the C.A.B. and C.A.A. are explained and the influence and form of State control and assistance to the operators over the years is traced.

Other sections of the book discuss airline finance, fares and rates and air freighting. There is even a short chapter on helicopter operations.

With all this apparent thoroughness, it is surprising to find in a book of this scope only one chapter—and that of a mere twenty pages—devoted to "Equipment and Maintenance." In view of the fact that the equipment used is surely the most important single factor in the whole business of air transport, it is disappointing to find that this vitally important field of the development, choice and characteristics of the vehicle are dismissed in but a few words. The crucial issues of aircraft economics and their payload/range characteristics in relation to the network operated are not even properly defined. For completeness, one feels that there should also have been more than just a passing mention of the future of turbine power.

Apart from the lack of attention to the equipment side of the business, this book can be thoroughly recommended. No interested reader can fail to learn a great deal from the mass of material attractively and conveniently presented and interpreted.

THE OBSERVER'S BOOK OF AIRCRAFT. William Green and Gerald Pollinger. Frederick Warne. London. 1952. 280 pp. 278 illustrations. 5s. net.

This is a new edition of an aircraft recognition pocket book which first appeared more than ten years ago. In its original form this book was far from satisfactory. In spite of its convenient size and attractive layout, neither the text nor the illustrations of the original edition set standards of accuracy appropriate to a reference book.

A revised edition compiled like the first by "Joseph Lawrence," was reviewed in the JOURNAL nearly three years ago. This was a marked improvement on the earlier volume but nevertheless still left a good deal to be desired in a number of its features.

The edition just published—now compiled by William Green and Gerald Pollinger—has at last achieved the necessary accuracy of text and illustration for it to be unreservedly recommended. As now produced, it represents a remarkable five shillings-worth in these days of high publication costs. In all, some 164 different types of aircraft are described and illustrated on good quality paper, the majority by both a photograph and three-view silhouettes. The photographs are, for the most part, well chosen and the silhouettes—with one or two exceptions—are accurately drawn.

Good as this little book has now become, there is still scope for improvement and it is to be hoped that the publishers will seek an even higher standard in the further editions that will surely follow. It would be an advantage if each aircraft's design number, type, name and mark could be set out in a consistent manner. Similarly, still further rationalisation of the performance figures, weights and other characteristics should be possible. Wing areas should be quoted.

"The Observer's Book of Aircraft" has now become a very effective "poor man's Jane's." As such it is likely to appeal not only to the youthful enthusiasts but also to anybody concerned with aviation who requires a convenient pocket reference on the characteristics of the World's aircraft.

AEROPLANES AND AERO-ENGINES. Reprinted from *The Aeroplane*, Temple Press Ltd. London, 1952. 4s. 6d. net. *Third Edition.*

This book is a collection of the well known drawings originally published in *The Aeroplane*. There are sectional drawings of eighteen aircraft, two piston engines and five gas turbine engines. These are reproduced with the almost unbelievable amount of detail to which readers of *The Aeroplane* have by now become accustomed.

The average draughtsman must be left in considerable awe of the standards of pictorial accuracy achieved by men such as J. H. Clark, L. Cresswell, R. Cross, C. Hurford and T. Page.

DUNLOP AVIATION EQUIPMENT MANUAL. 140 pp. Illustrated. Dunlop Rubber Co.

This manual replaces the Dunlop Year Books published in 1951 and in previous years. Its intended purpose is to provide a survey of the Company's aviation products and this it does, in the simple and attractive way which is typical of many trade publications. In addition there are interesting and instructive notes on the fundamentals of the design, construction and testing of tyres, wheels and brakes, which would make good reading in any context; in this case, not unnaturally, the emphasis is on Dunlop.

FLAMES IN THE SKY. Pierre Clostermann, D.F.C. Translated by Oliver Berthoud. Chatto and Windus. London, 1952. 200 pp. 16 illustrations. 12s. 6d. net.

This is a collection of tales of the war in the air based upon facts uncovered by a historian in the course of a six-year search of Allied and enemy documents.* The historian, himself an active participator in that war—*vide* his book, "The Big Show"—knowing how small a place examples of human courage can be given in a wide survey of events involving millions of individuals, has saved from burial by documentation nine incidents, each reflecting an act of heroism.

Clostermann is an artist with words. In this book he adds the bright imagination of the novelist to the great descriptive powers he disclosed in "The Big Show." Combing the two talents, and drawing upon his own experience, he is able to fill in the sequences which official records leave blank. For instance, a Mosquito takes off and is not heard of again until, its mission completed, it crashes in flames. But the reader is in the cockpit every minute of that desperate flight. And what a thrilling ride he gets! Here and there, the picture seems to be slightly over-drawn—a shade too colourful for the occasion.

Young readers will bless the author for including some biographical notes about the aeroplanes in which the gallant deeds were enacted.

*Clostermann has recently completed a History of the War in the Air, a project he set his heart on in 1940.

ESCAPE—OR DIE. Paul Brickhill. Evans Brothers Ltd. London. 1952. 223 pp. Illustrated. 15s. net.

At the end of the recent war the Royal Air Force Escaping Society was formed under the chairmanship of Air Marshal Sir Basil Embry, with the object of expressing and re-paying something of the indebtedness owed by the R.A.F. to those who assisted them to escape from the enemy, and particularly the widows and orphans of those who died trying to help R.A.F. crews in France, Belgium, Holland, Italy and in the Far East. To that end Paul Brickhill, renowned for his thrilling *Dam Busters* and *The Great Escape*, has written eight stories comprising this new book, the sales of which will help to provide funds for the work of the Escaping Society. To purchase and read *Escape—or Die* is therefore not only to indulge in stirring excitement, but is also a direct expression of assistance to the many unsung civilians who so courageously helped the brave to return and fight another day.

In a most interesting foreword, H. E. Bates, with quick perception, analyses the special attitude of the R.A.F. towards captivity and the impetus to escape. It was not necessarily braver, more ingenious, more determined or more resourceful than that shown by men in other services—but it was formed by a set of circumstances that had never applied to a British fighting force in wartime before. "Whereas in other wars men had gone out from Britain to tackle enemies well out of sight of home, the R.A.F. now found itself having tea in the calm summer air of an English village at 4 o'clock, fighting in a highly specialised theatre of its own at 20,000 ft. at half past, and returning to take a telephone call from an inquiring girl-friend at five . . . It made them when captured, the most reluctant of prisoners; it was suddenly very annoying not to be able to ride home for tea; it was absolutely infuriating to be keeping a date with a Nazi rifle instead of one with a brunette in a café at Canterbury."

Paul Brickhill, with all the skill of a trained writer, fired by knowledge of his own experience of captivity behind the wires, grasps the very essence of the escapers' spirit in the pure cussedness, grit, and determined refusal to lie down when dead. His title story, horrifying and amazing, comprising a quarter of the book, is such an epic in itself, that any other story must stand grave risk of being overshadowed; yet each easily manages to wear an individual character, so widely different and so audacious are the circumstances of escape.

With every story a photograph and a few introductory lines of biography up to the moment of the flight preceding the escape helps in envisaging the central character, while a brief and interesting epilogue gives the subsequent history to date. While adding a touch of vivid contrast to the main theme, it is a method reminiscent of the studied understatement which the R.A.F. brought to so high a pitch of refinement—but then, of course, the whole book is a unique expression of the age-old British reluctance to make a fuss about things that are a little abnormal to the everyday matters of life.

THE CROWDED HOURS. Anthony Richardson. Max Parrish. London. 1952. 247 pp. 15s. 6d. net.

The use of a fragmentary episode, from a war-time operational flight, as a literary device to present a life story dealing principally with South Africa would be insufficient justification for the insertion of this review in the JOURNAL were it not that this book is a tribute to a courageous man who flew with the R.A.F. in World War II instead of sticking to a ground job as liaison officer at the Admiralty. Wing Commander Lionel ("Sos") Cohen, D.S.O., M.C., must be the oldest recipient of the D.F.C., for it was awarded to him in his seventieth year, after 70 operational flights in which he took part as observer.

There is very little about flying in this book, apart from a quartet of italicised pages, a somewhat inaccurate account of an early balloon flight, and a short description of flying in Africa during 1916 with the Voisins of the R.N.A.S. Instead it describes the early, unsettled and adventurous history of "Sos," made exciting with Matabele spears, sentence of death, man-eating ants, lions, Boer Commandos, and a green mamba's bite. Three-quarters of the book are occupied with his first twenty years after leaving school, but the next twenty-three are compressed into the remainder with only a single further page to take the reader from 1926 to 1939, at which the last brief section of the linking episode concludes the story.

It is a biography of highlights contrived with too much artifice to be outstanding, yet Anthony Richardson is sufficiently successful in evoking appreciation of his hero's fighting spirit to make one wish that more of the mature man could have been revealed. Adventure might diminish to the no less formative story of an enterprising stockbroker whose hobby was farming, but it is against the background of everyday things that a philosophy is tested. Though *The Crowded Hours* may fail to express the full calibre of Cohen, none can deny that in the cold deliberation of modern war his courage was proved to be identical with all those young men who had taken him to their hearts "among the very brave, the very true."

FAITH IS A WINDSOCK. Miles Tripp. Peter Davies. 1952. 223 pp. 12s. 6d. net. *Fiction.*

This novel makes an interesting contrast to "The Happy Valley," reviewed in the May JOURNAL. It is delightfully free from introspective musings and the crew of "G for George" strike one as being fairly normal men. Nevertheless, having read three stories in succession about bomber crews I fear that authors choosing them as their themes are finding difficulty in producing anything very original. The inevitable females brought in for "colour" are all much the same and since air crews usually remain teamed throughout a tour it is difficult to get a new "angle" on character sketches.

Mr. Tripp tends to use rather too many technical terms which confuse the uninitiated reader, and I do wish that when "Service" writers wish to use a really naughty word they would not give a thinly disguised version of it. It would be far better to leave it out altogether.

PIONEER PILOT. William Armstrong. Blandford Press. London. 1952. 267 pp. Illustrated. 15s. net.

Captain Armstrong's story is that of one of the first commercial air line pilots. After service in the First World War in bombers he became a civil pilot with the Aircraft Transport and Travel Company operating the London-Paris service. From that time, except for a period of just over three years, he has played his part—and enjoyed playing it—in the development of civil aviation as we know it today.

The reader will put the book down with two major convictions, firstly that flying today is much safer than it used to be and secondly that there is still at least one job left where one can have "adventures" in the classical sense.

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INDEX TO VOL. LVI

AERODROME PAVEMENTS
See Runways

AERODYNAMIC CENTRE
See A. H. Yates

AERODYNAMICS
A Shortened Method for the Calculation of Aerofoil Profile Drag, E. M. Dowlen, p. 109 (Feb.).
Notes on the Mean Aerodynamic Chord and the Mean Aerodynamic Centre of a Wing, A. H. Yates, p. 461 (June).

AEROELASTICITY
See also H. H. Gardner.
A Method of Estimating the Loading on an Elastic Airframe, B. A. Hunn, p. 261 (April). Correction p. 318 (May).

AERONAUTICAL INFORMATION
The Availability and Use of Aeronautical Information—A Discussion, p. 411 (June).

AERONAUTICAL SOCIETY, ROYAL
See Royal Aeronautical Society.

AERONAUTICS
Prophecy and Achievement in Aeronautics, Sir Harry M. Garner, p. 493 (July).

AEROPLANES—DESIGN AND CONSTRUCTION
See also Transonic Flight and H. H. Gardner.
Design Problems for Interceptor Fighters, J. S. Bailey, p. 438 (June). Correspondence pp. 729-31 (Sept.).
Production Research on Aircraft, L. E. Bunnett, p. 179 (March). Correspondence pp. 478-9 (June).
Some Aspects of Aircraft Design and Manufacture for Limited Production, W. S. Hollyhock, p. 25 (Jan.).
Structural Problems of Advanced Aircraft, H. H. Gardner, p. 221 (April).

AGRICULTURE
Aircraft in Agriculture, P. H. Southwell, p. 33 (Jan.).

AIRCRAFT DESIGN
See Aeroplanes—Design and Construction, Transonic Flight and H. H. Gardner.

AIR TRAFFIC CONTROL
See E. A. Whiteley.

AIR TRANSPORT
See also Airworthiness.
Civil Aviation in the Second Elizabethan Era, G. N. Roberts, p. 849 (Nov.).
Problems of Short-Haul Air Transport, P. W. Brooks, p. 441 (June).
Graphical Analysis of Trans-Canada Airlines' Progress on the North American Routes 1946-1950, A Jaworski, p. 382 (May).
Some Operating Problems of Future Transport Aircraft, C. Dyke, p. 189 (March).
The Spacing of Aircraft under High Density Approach Conditions, E. A. Whiteley, p. 573 (Aug.).

AIRWORTHINESS
Maintaining Airworthiness in Operation, R. E. Hardingham, p. 819 (Nov.).
Modern Trends in Civil Airworthiness Requirements, W. Tye, p. 73 (Feb.).

ANNUAL REPORT
See Royal Aeronautical Society.

ASHWELL, D. G.
The Stability in Bending of Slightly Corrugated Plates, p. 782 (Oct.).

ASLIB
See Aeronautical Information.

AWARDS AND MEDALS
See Royal Aeronautical Society.

BAILEY, J. S.
Design Problems for Interceptor Fighters, p. 438 (June). Correspondence pp. 729-731 (Sept.).

BALL BEARINGS
Oscillatory Occurrences in Ball Bearings, M. S. Frenkel, p. 885 (Dec.).

BLACK, JOSEPH
A Note on the Vortex Patterns in the Boundary Layer Flow of a Swept-Back Wing, p. 279 (April).

BLACK, R. A. R.
The Application of Plastics to Aircraft, p. 47 (Jan.).

BLERIOT, LOUIS, FIFTH LECTURE
Fifth Louis Bleriot Lecture—The Future of the Flying Boat, Henry Knowler, p. 322 (May).

BLINKHORN, J. W.
Loads on Multi-Wheel Undercarriages During Ground Manoeuvring and Take-Off, p. 547 (July).

BOUNDARY LAYER
Note on the Vortex Patterns in the Boundary Layer Flow of a Swept-Back Wing, Joseph Black, p. 279 (April).

BRITISH COMMONWEALTH AND EMPIRE—EIGHTH LECTURE
Maintaining Airworthiness in Operation, R. E. Hardingham, p. 819 (Nov.).

BROADBENT, E. G. and W. T. KIRKBY
Control Surface Flutter, p. 355 (May).

BROOKS, P. W.
Problems of Short-Haul Air Transport, p. 441 (June).

BUNNETT, L. E.
Production Research on Aircraft, p. 179 (March). Correspondence pp. 478-9 (June).

BUXTON, G. M.
Problems of Servicing and Reliability, p. 869 (Dec.).

CASSIE, W. FISHER
The Influence of Tyre Pressure on the Design of Aerodrome Pavements, p. 691 (Sept.).

CLIFTON, A. N.
Problems of Transonic Flight, p. 155 (March).

CONTROLS
See Flutter and Power Controls.

CORRESPONDENCE
Design for Maintenance.
L. S. Ash, p. 207 (March).
Design Problems for Interceptor Fighters.
R. K. Page, p. 729 (Sept.).
G. S. Henson, p. 730 (Sept.).
Fellowship of the Air (Review in Dec. 1951 Journal).
B. J. Hurren, p. 141 (Feb.).
Production Research.
Aldric B. Au-Yong, p. 478.
L. E. Bunnett, p. 479.
Resonance Testing and Flutter Calculations.
N. C. Lambourne.
C. P. Plantin, p. 311 (April).
Structures Data Sheets.
J. H. Argyris and P. C. Dunne, p. 801 (Oct.).

CORRUGATED PLATES
See D. G. Ashwell.

COUNCIL REPORT
See Royal Aeronautical Society.

CUSSONS, R. C.
Bogie Undercarriages, p. 536 (July).

DESIGN
See Aeroplanes—Design and Construction, Transonic Flight and H. H. Gardner.

DEVEREUX, WALLACE CHARLES (OBITUARY)
p. 571 (Aug.).

DRAG
See Aerodynamics.

DOWLEN, E. M.
A Shortened Method for the Calculation of Aerofoil Profile Drag, p. 109 (Feb.).

DOWTY, GEORGE H.
President, Royal Aeronautical Society, 1952-1953, p. 402 (June).

DYKES, C.
Some Operating Problems of Future Transport Aircraft, p. 189 (March).

ENGINES
See Gas Turbines.

FATIGUE
Fatigue Life of Wing Components for Civil Aircraft, Keri Williams, p. 842 (Nov.).
Fatigue of Aircraft Materials with Special Reference to Micro-Structure, P. L. Teed, p. 427 (June).
Structural Problems of Advanced Aircraft, H. H. Gardner, p. 221 (April).

FLYING BOATS
The Future of the Flying Boat, H. Knowler, p. 322 (May).

FLUTTER
Control Surface Flutter, E. G. Broadbent and W. T. Kirkby, p. 355 (May).
The Technique of Resonance Testing and Flutter Calculations as Applied to Fighter Aircraft Design, C. P. Plantin, p. 117 (Feb.). Correspondence, p. 311 (April).

FUEL SYSTEMS
Fuel Systems for Turbine-Engined Aircraft, J. E. Walker, p. 657 (Sept.).

FRENKEL, M. S.
Oscillatory Occurrences in Ball Bearings, p. 885 (Dec.).

GARDEN PARTY—1952
P. 639 (Aug.).

GARDNER, H. H.
Structural Problems of Advanced Aircraft, p. 221 (April).

GARNER, SIR HARRY M.
Prophecy and Achievement in Aeronautics—40th Wilbur Wright Memorial Lecture, p. 493 (July).

GAS TURBINES
Air Intakes for Aircraft Gas Turbines, J. Seddon, p. 747 (Oct.).
Fuel Systems for Turbine-Engined Aircraft, J. E. Walker, p. 657 (Sept.).

GORDON, J. E.
On the Present and Potential Efficiency of Structural Plastics, p. 704 (Sept.).

HANCOCK, K. G. and P. PERSON
Power Steering for Aircraft, p. 513 (July).

HARDINGHAM R. E.
Maintaining Airworthiness in Operation—Eighth British Commonwealth and Empire Lecture, p. 819 (Nov.).

HODGSON, JOHN EDMUND (OBITUARY)
P. 319 (May).

HOLLYHOCK, W. S.
Some Aspects of Aircraft Design and Manufacture for Limited Production, p. 25 (Jan.).

HUNN, B. A.
A Method of Estimating the Loading on an Elastic Airframe, p. 261 (April). Correction, p. 318 (May).

INTAKES
Air Intakes for Aircraft Gas Turbines, J. Seddon, p. 747 (Oct.).

JACKSON, C. H.
Some Notes on Aircraft Overhaul and Maintenance, p. 619 (Aug.).

JAWORSKI, ADAM
Graphical Analysis of Trans-Canada Airlines' Progress on the North American Routes, 1946-50, p. 382 (May).

JOY, C. F.
Power Controls for Aircraft, p. 7 (Jan.).

KIRKBY, W. T. and E. G. BROADBENT
Control Surface Flutter, p. 355 (May).

KNOWLER, HENRY
The Future of the Flying Boat—Fifth Louis Bleriot Lecture, p. 323 (May).

LECTURE SPEAKERS
See Royal Aeronautical Society.

LONGITUDINAL MANOEUVRES
See Tail Loads.

MAINTENANCE
Problems of Servicing and Reliability, G. M. Buxton, p. 869 (Dec.).
Some Notes on Aircraft Overhaul and Maintenance, C. H. Jackson, p. 619 (Aug.).

MATERIALS
See also Plastics.
Fatigue of Aircraft Materials with Special Reference to Micro-Structure, P. L. Teed, p. 427 (June).
Structural Problems of Advanced Aircraft, H. H. Gardner, p. 221 (April).

MEAN CHORD
See A. H. Yates.

METALS
See Materials and Fatigue.

NAVAL OPERATIONS
Design Problems for Interceptor Fighters, J. S. Bailey, p. 438 (June). Correspondence, pp. 729-31 (Sept.).

NEW ZEALAND DIVISION
Third Annual Report, p. 392 (May).

OPERATING PROBLEMS
See Air Transport.

PERSON, P. and K. G. HANCOCK
Power Steering for Aircraft, p. 513 (July).

PLANNING
See Aeroplanes—Design and Construction.

PLANTIN, C. P.
The Technique of Resonance Testing and Flutter Calculations as Applied to Fighter Aircraft Design, p. 117 (Feb.). Correspondence, p. 311 (April).

PLASTICS
On the Present and Potential Efficiency of Structural Plastics, J. E. Gordon, p. 704 (Sept.).
The Application of Plastics to Aircraft, R. A. R. Black, p. 47 (Jan.).

POWER CONTROLS
Power Controls for Aircraft. C. F. Joy, p. 7 (Jan.).

PRODUCTION
See Aeroplanes—Design and Construction.

REA, J. B. and G. W. SMITH
Aeroplane Tail Loads for Longitudinal Manoeuvres, p. 789 (Oct.).

RESEARCH
See Aerodynamics and Transonic Flight.

RESONANCE TESTING
See Flutter and H. H. Gardner.

REVIEWS
A.B.C. of Gliding, The, Fox Geen, p. 807 (Oct.).
A.B.C. of Model Aircraft Construction, The, F. Callon, p. 911 (Dec.).
Adhesion and Adhesives, N. A. de Bruyne and R. Houwink, p. 203 (March).

Adhesives for Wood, R. A. G. Knight, p. 305 (April).
Advanced National Certificate Mathematics, J. Pedoe, p. 645 (Aug.).
Advanced Strength of Materials, D. A. R. Clark, p. 201 (March).
Aeronautical Engineering Index 1951, Institute of the Aeronautical Sciences, p. 913 (Dec.).
Aerodynamic Drag, Sighard F. Hoerner, p. 557 (July).
Aerodynamics of Supersonic Flight, Alan Pope, p. 139 (Feb.).
Aerodynamics of the Helicopter, Gesson and Myers, p. 855 (Nov.).
Aeroplanes and Aero-engines, *The Aeroplane*, p. 915 (Dec.).
Air League Aircraft Recognition Manual, The, C. H. Gibbs-Smith, p. 647 (Aug.).
Air Navigation — Theory and Practice, E. Brook Williams and W. J. V. Branch, p. 910 (Dec.).
Air Power Key to Survival, Alexander P. de Seversky, p. 733 (Sept.).
Air Transport in Australia, D. M. Hocking and C. P. Haddon Cave, p. 647 (Aug.).
Air Transportation Management, J. L. Nicholson, p. 914 (Dec.).
Aircraft Engines of the World 1952, Paul H. Wilkinson, p. 913 (Dec.).
Aircraft Gyroscopic Flight Instruments, Sperry Gyroscope Co. Ltd., p. 397 (May).
Aircraft Maintenance, D. J. Brimm and H. E. Boggess, p. 735 (Sept.).
Aircraft Materials and Processes, George F. Titterton, p. 397 (May).
Air-plane Flight, A. York-Bramble, p. 854 (Nov.).
Airplane Design Manual, Frederick K. Teichmann, p. 856 (Nov.).
Airplane Aerodynamics, D. O. Dommasch, p. 204 (March).
Algebra of Vectors and Matrices, The, Thomas L. Wade, p. 306 (April).
Analysis of the Four-Bar Linkage, John A. Hrones and George R. Nelson, p. 305 (April).
Automatic and Manual Control, Ed. by A. Tustin, p. 805 (Oct.).
Automatic Feedback Control, Ahrendt and Taplin, p. 854 (Nov.).
Aviation Insurance, E. G. Ingram, p. 559 (July).
Aviation Medicine, Harry G. Armstrong, p. 911 (Dec.).
Ballistics in the Seventeenth Century, A. R. Hall, p. 856 (Nov.).
Baughman's Aviation Dictionary and Reference Guide, E. J. Gentle and C. E. Chapel, p. 308 (April).
Behaviour of Engineering Metals, The, H. W. Gillett, p. 201 (March).
Bibliographical Survey of Flow through Orifices and Parallel-Throated Nozzles, T. H. Redding, p. 733 (Sept.).
Calibration of Commercial Radio Field-Strength Meters at the National Bureau of Standards, Frank M. Greene, p. 397 (May).
Carburation (Applied Carburation and Petrol Injection), Vol. 1, Charles H. Fisher, p. 58 (Jan.).
Carburation, Vol. 2, Charles H. Fisher, p. 646 (Aug.).
Combustion, Flames and Explosions of Gases, Bernard Lewis and G. von Elbe, p. 59 (Jan.).
Classical Mechanics, Herbert Goldstein, p. 204 (March).
Crispin's Day, Leigh Howard, p. 309 (April).
Crowded Hours, The, Anthony Richardson, p. 916 (Dec.).
Design of Machine Members, Vallance and Doughtie, p. 646 (Aug.).
Development of the Guided Missile, Kenneth W. Gatland, p. 911 (Dec.).
Dimensional Analysis and Theory of Models, L. Langmaar, p. 57 (Jan.).
Dunlop Aviation Manual, p. 915 (Dec.).
Elements of Statistics, C. G. Lambe, p. 735 (Sept.).
English-French Vocabulary of Aeronautical Terms, M. Chalmette, p. 397 (May).
Escape or Die, Paul Brickhill, p. 915 (Dec.).
Faith is a Windsock, Miles Tripp, p. 916 (Dec.).
Fated Sky, The, Air Chief Marshal Sir Philip Joubert de la Ferté, p. 912 (Dec.).
Finite Deformation of an Elastic Solid, Francis D. Murnaghan, p. 805 (Oct.).
Flames in the Sky. Pierre Clostermann, p. 915 (Dec.).
Flight Eastward, John Fores, p. 397 (May).
Fundamentals of Automatic Control, G. H. Farrington, p. 644 (Aug.).
Gas Turbine Theory, Cohen and Rogers, p. 307 (April).
Handbook of Aerial Mapping and Photogrammetry, Lyle G. Trorey, p. 910 (Dec.).
Handbook of Agricultural Pest Control, S. F. Bailey and L. M. Smith, p. 206 (March).
Happy Valley, The, Jules Roy, p. 398 (May).
Heat and Thermodynamics, Mark W. Zemansky, p. 308 (April).
Helicopter Analysis, A. A. Nikolsky, p. 804 (Oct.). Correction, p. 909 (Dec.).
Hiduminium Technical Data, p. 855 (Nov.).
High-Speed Aerodynamics, W. F. Hilton, p. 804 (Oct.).
Index Bibliographicus, Vol. 1, Science and Technology, Theodore Besterman, p. 559 (July).
Initiation and Growth of Explosions in Liquids and Solids, The, F. P. Bowden and A. D. Yoffe, p. 807 (Oct.).
Internal Combustion Engines, Lester C. Lichty, p. 60 (Jan.).
Introduction to the Study of Aircraft Vibration and Flutter, Robert H. Scanlan and Robert Rosenbaum, p. 59 (Jan.).
Jane's All the World's Aircraft 1951/52, Ed. by L. Bridgman, p. 203 (March).
Khaki and Blue, R. Sherbrooke-Walker, p. 912 (Dec.).
Marshal Without Glory, Ewan Butler and Gordon Young, p. 205 (March).
Mathematical Engineering Analysis, R. Oldenburger, p. 57 (Jan.).
Mechanics Applied to Vibrations and Balancing, D. Laugharne Thornton, p. 140 (Feb.).
Mechanics of Vibration, Holger M. Hansen and Paul F. Chenea, p. 909 (Dec.).
Military Aircraft of the U.S.S.R., Charles W. Cain and Denys J. Voaden, p. 396 (May).
Navigation—Theory and Practice, E. Brook Williams and W. J. V. Branch, p. 910 (Dec.).
Net, The, John Pudney, p. 808 (Oct.).
Night Be My Witness, W. Clapham, p. 808 (Oct.).

Observer's Book of Aircraft, F. Warne, p. 914 (Dec.).
Parachutes, W. D. Brown, p. 202 (March).
Physics of Lubrication—A Symposium (British Rheologist's Club and the Institute of Physics), p. 139 (Feb.).
Pioneer Pilot, William Armstrong, p. 916 (Dec.)
Powder Metallurgy, Vol. 9, C. J. Leadbeater and others, p. 732 (Sept.).
Principles of Control and Stability of Aircraft, W. J. Duncan, p. 557 (July).
Principle and Practice of Aviation Medicine, Harry G. Armstrong, p. 911 (Dec.).
Production Engineering Administration and Management, J. V. Connolly, p. 307 (April).
Protection and Electro-Deposition of Metals, L. F. Le Brocq and others, p. 732 (Sept.).
Radio Astronomy, Bernard Lovell and J. A. Clegg, p. 736 (Sept.).
Selected Government Research Reports, Vol. 5, Servo-Mechanisms, p. 644 (Aug.).
Shawcross and Beaumont on Air Law, Christopher N. Shawcross, K. M. Beaumont and Patrick R. E. Browne, p. 558 (July).
Stories of Flying Officer "X," The, H. E. Bates, p. 808 (Oct.).
Strain Gauges—Theory and Application, J. J. Koch *et al*, p. 645 (Aug.).
Structural Adhesives—The Theory and Practice of Gluing with Synthetic Resins, p. 643 (Aug.).
Stuka Pilot, Hans Ulrich Rudel, p. 736 (Sept.).
Symposium on Welding and Riveting Larger Aluminium Structures, p. 806 (Oct.).
Synthetic Resins and Allied Plastics, R. S. Monnell and H. M. Langton, p. 643 (Aug.).
Tedder, Roderic Owen, p. 648 (Aug.).
Theoretical Aerodynamics, L. M. Milne-Thomson, p. 805 (Oct.).
Theory and Technique of Soaring, John Kukuski, p. 734 (Sept.).
Theory of Elasticity (New Edition), Timoshenko and Goodier, p. 308 (April).
Theory of Perfectly Plastic Solids, W. Prager and P. G. Hodge, Jun., p. 396 (May).
Traité Elémentaire de Droit Aérien, Michel de Juglart, p. 806 (Oct.).
Typical Helicopter Performance Calculation, R. J. Harris, L. H. Sloan and K. W. Ulrich, p. 735 (Sept.).
Vibration and Shock Isolation, Charles E. Crede, p. 306 (April).
Welding Methods and Tests—Welding Practice, Vol. 1, E. Fuchs and H. Bradley, p. 559 (July).
White Rabbit, The, Bruce Marshall, p. 648 (Aug.).

ROBERTS, G. N.

Civil Aviation in the Second Elizabethan Era, p. 849 (Nov.).

ROYAL AERONAUTICAL SOCIETY

Acknowledgments, pp. 5, 70, 152, 219, 319, 410.
Additions to the Library, pp. 61, 142, 210, 309, 398, 475, 561, 649, 737, 809, 857, 917.
Aeronautical Trusts Ltd., Balance Sheet, p. 296 (April).
Annual Report of Council 1951-1952 (87th), p. 286 (April).
Journal Binding, p. 814 (Nov.).
Branches, p. 404 (June).
Associate Fellowship Examinations—Results, p. 151 (March), p. 568 (Aug.).
Council 1952-1953, p. 401 (June), p. 481 (July).
Devereux, Wallace Charles (Obituary), p. 571 (Aug.).
Dowty, George H.—President 1952-1953, p. 402 (June).
Elections, pp. 5, 71, 152, 218, 317, 410, 488, 569, 655, 746, 818, 867.
Elliott Memorial Prize, p. 218 (April), p. 488 (July), 868 (Dec.).
Fellows, Election of, p. 408 (June).
Garden Party 1952, p. 639 (Aug.).
Her Majesty Queen Elizabeth II, Patron of the Society, p. 482 (July).
His Late Majesty King George VI, p. 145 (March).
Hodgson, John Edmund (Obituary), p. 319 (May).
Honours Awarded to Members, pp. 4, 148, 218, 316, 409, 487, 566, 654, 815.
Journal Premium Awards (1951), p. 316 (May).
Medals and Awards, List of, p. 484 (July).
Presentation, p. 490 (July).
Memorial to Sir John Alcock and Sir Arthur Whitten Brown, p. 656 (Sept.).
New Zealand Division—Third Annual Report (1951), p. 392 (May).
Royal Aeronautical Society, Balance Sheet, p. 294 (April).
S.B.A.C. Educational Grants, p. 746 (Oct.).
Scholarships, p. 70.
The Secretary's News Letter, pp. 1, 65, 213, 313, 405, 485, 565, 653, 741, 813, 861.

Lecture Speakers

Allwright, E. S., p. 685 (Sept.); Annand, W. J., p. 174 (March), p. 777 (Oct.); Bailey, H. N. D., p. 531 (July); Baxter, A. D., p. 414 (June); Bentley, E. N. B., p. 102 (Feb.); Broadbent, E. G., p. 379 (May); Campion, L. F., p. 683 (Sept.); Carlisle, E. L., p. 684 (Sept.); Ciastula, T. L., p. 175 (March); Cleverdon, Cyril, pp. 412, 424 (June); Clifton, A. N., p. 176 (March); Collar, A. R., p. 375 (May); Conway, H. G., pp. 528, 532 (July); Crampton, H. J., p. 102 (Feb.); Cuss, J. F., p. 172 (March); Cussons, R. C., p. 529 (July); Davies, Handel, p. 171 (March); Dowty, G. H., p. 175 (March); Ebbutt, C. G. W., p. 415 (June); Ellis, G. H., p. 379 (May); Ellison, A. E., pp. 529, 531 (July); Ewans, J. R., p. 175 (March); Felgate, P. E., p. 684 (Sept.); Fischeles, E. S., p. 617 (Aug.); Fisher, W. A. P., p. 257 (April); Foster, —., p. 532 (July); Fraenkel, L. E., p. 778 (Oct.); Fraser, D. O., pp. 615, 616 (Aug.); Gardner, H. H., p. 98 (Feb.), p. 258 (April); Gibson, Wing Cdr. G. P., p. 104 (Feb.); Greatrex, F. B., p. 773 (Oct.); Griffiths, J. W., p. 421 (June); Hall, A. A., pp. 411, 424 (June); Hancock, K. G., p. 533 (July); Hardingham, R. E., p. 97 (Feb.); Hardman, J., p. 378 (May); Havard, E. G., p. 174 (March); Henson, G. S., p. 417 (June); Hilton, W. F., p. 173 (March); Holland, C. D., p. 530 (July); Holloway, C. F., p. 682 (Sept.); Hollyhock, W. S., p. 423 (June); Howard, H. B., p. 254 (April); Jones, B. D., p. 420 (June); Jones, K. Paton, p. 618 (Aug.); Keen, E. D., p. 255 (April); King, J. C., p. 682 (Sept.); Kirk, J. A., p. 418 (June); Kirkby, W. T., p. 381 (May);

Küchemann, D., p. 422 (June), p. 778 (Oct.); Laight, B. P., p. 172 (March); Lambert, D. J., p. 103 (Feb.); Lane, J. W., p. 423 (June); Lee, G. H., p. 254 (April); Lickley, R. L., p. 252 (April), p. 416 (June); March, H. M., p. 618 (Aug.); Masefield, P. G., p. 99 (Feb.); McDonald, E., p. 530 (July); Mettam, H. A., p. 256 (April); Molyneux, W. G., p. 379 (May); Morgan, R. C., p. 252 (April); Moss, E. B., p. 684 (Sept.); Neilson, C. B. V., p. 531 (July); North, J. D., p. 100 (Feb.); O'Farrell, M., p. 681 (Sept.); Owner, F. M., p. 776 (Oct.); Person, P., p. 533 (July); Pollicutt, F. H., p. 254 (April); Pribram, E., p. 776 (Oct.); Prower, C. W., p. 531 (July); Pugsley, A. G., p. 256 (April), p. 376 (May); Ratcliffe, G., p. 105 (Feb.); Redshaw, S. C., p. 173 (March); Rogerson, H. G., p. 529 (July); Rowe, N. E., p. 175 (March), p. 684 (Sept.); Roxbee Cox, Dr. H., p. 96 (Feb.), p. 250 (April); Rulikowski, G. Korab, p. 104 (Feb.); Seddon, J., p. 779 (Oct.); Serby, J. E., p. 776 (Oct.); Slocombe, A. E., p. 616 (Aug.); Smedley, F. E. S., p. 686 (Sept.); Stables, E. R., p. 101 (Feb.); Stafford, R. S., p. 253 (April); Staite, H. J., p. 377 (May); Stewart, Group Capt. W. K., p. 98 (Feb.); Still, E. W., p. 685 (Sept.); Tatham, R., p. 255 (April); Templeton, H, p. 377 (May); Thorne, R. G., pp. 423, 425 (June); Toms, C. F., p. 779 (Oct.); Tye, W., p. 106 (Feb.); Walker, J. E., p. 688 (Sept.); Walters, I. F. B., p. 616 (Aug.); Warde, R. H., p. 681 (Sept.); Webb, G. F., p. 420 (June); Whiteley, E. A., pp. 615-618 (Aug.); Willey, E. S., p. 617 (Aug.); Williams, Dr., p. 251 (April); Winny, H. F., p. 174 (March), p. 378 (May); Wolfe, M. O. W., p. 379 (May).

RUNWAYS

The Design and Construction of Airfield Pavements, M. J. Tomlinson, p. 877 (Dec.).

The Influence of Tyre Presure on the Design of Aerodrome Pavements, W. Fisher Cassie, p. 691 (Sept.).

SEDDON, J.

Air Intakes for Aircraft Gas Turbines, p. 747 (Oct.).

SMITH, G. W. and J. B. REA

Aeroplane Tail Loads for Longitudinal Manoeuvres, p. 789 (Oct.).

SOUTHWELL, P. H.

Aircraft in Agriculture, p. 33 (Jan.).

STRUCTURES

See also Plastics.

Note on the Ultimate Strength of Webs in Shear, R. Tatham, p. 701 (Sept.).

Structural Problems of Advanced Aircraft, H. H. Gardner, p. 221 (April).

The Stability in Bending of Slightly Corrugated Plates, D. G. Ashwell, p. 782 (Oct.).

SWEEPBACK

See Boundary Layer.

TAIL LOADS

Aeroplane Tail Loads for Longitudinal Manoeuvres, G. W. Smith and J. B. Rea, p. 789 (Oct.).

TATHAM, R.

Note on Ultimate Strength of Webs in Shear, p. 701 (Sept.).

TEED, P. L.

Fatigue of Aircraft Materials with Special Reference to Micro-Structure, p. 427 (June).

TOMLINSON, M. J.

The Design and Construction of Airfield Pavements, p. 877 (Dec.).

TRANSFER FUNCTIONS (T.F.F. METHOD)

See Tail Loads.

TRANSONIC FLIGHT

Problems of Transonic Flight, A. N. Clifton, p. 155 (March).

TYE, WALTER

Modern Trends in Civil Airworthiness Requirements, p. 73 (Feb.).

TYRE PRESSURE

See Runways.

UNDERCARRIAGES

Bogie Undercarriages, R. C. Cussons, p. 536 (July).

Loads on Multi-Wheel Undercarriages During Ground Manoeuvring and Take-Off, J. W. Blinkhorn, p. 547 (July).

Power Steering for Aircraft, K. G. Hancock and P. Person, p. 513 (July).

VORTEX PATTERNS

See Boundary Layer.

WALKER, J. E.

Fuel Systems for Turbine-Engined Aircraft, p. 657 (Sept.).

WHITELEY, E. A.

The Spacing of Aircraft Under High Density Approach Conditions, p. 573 (Aug.).

WILLIAMS, KERI

Fatigue Life of Wing Components for Civil Aircraft, p. 842 (Nov.).

WRIGHT, WILBUR

40th Memorial Lecture—Prophecy and Achievement in Aeronautics, Sir Harry M. Garner, p. 493 (July).

YATES, A. H.

Notes on the Mean Aerodynamic Chord and the Mean Aerodynamic Centre of a Wing, p. 461 (June).

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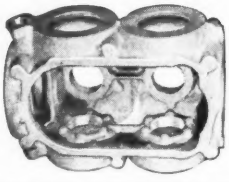

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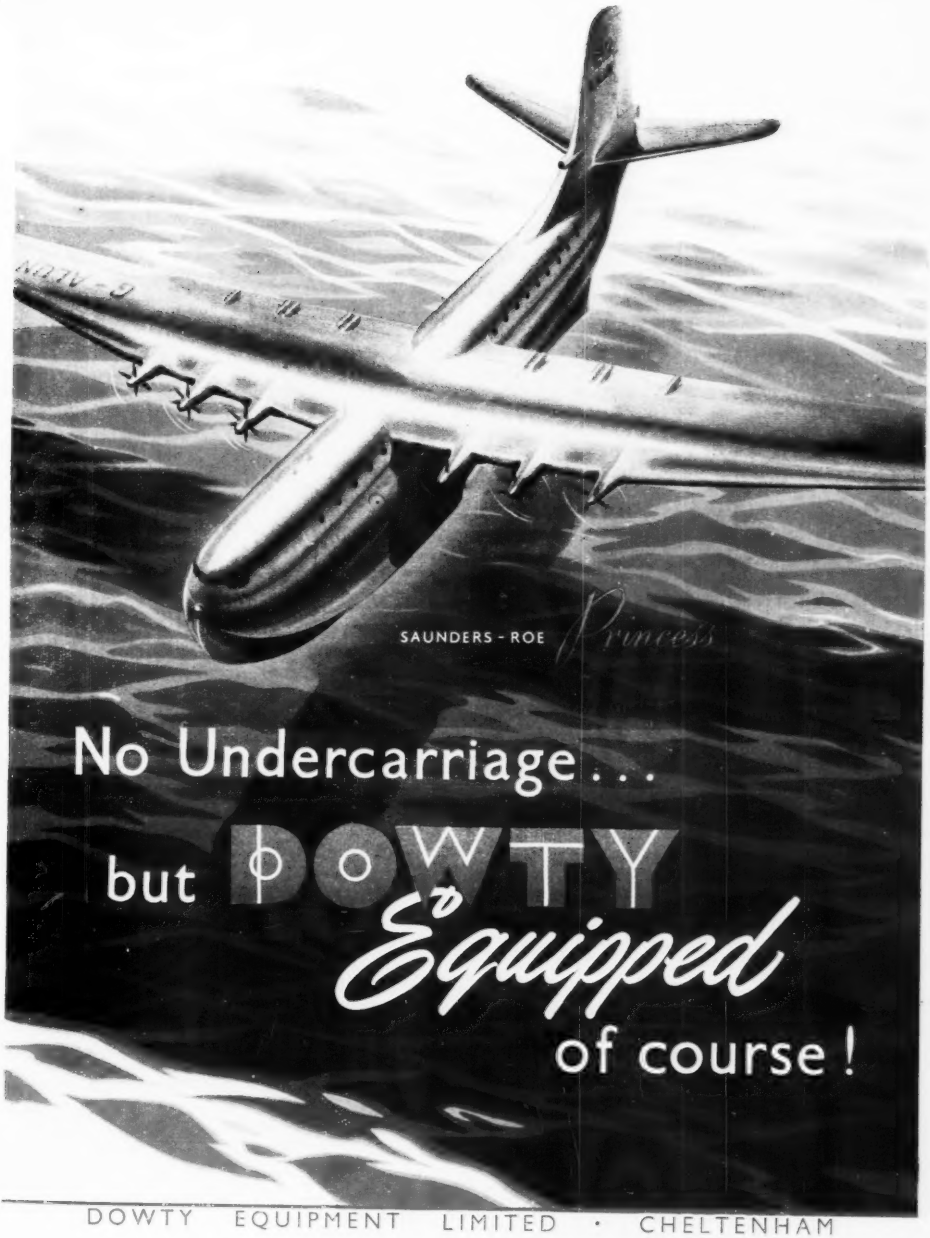

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